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RADAR IDENTIFICATION OF NAVAL VESSELS.(U)

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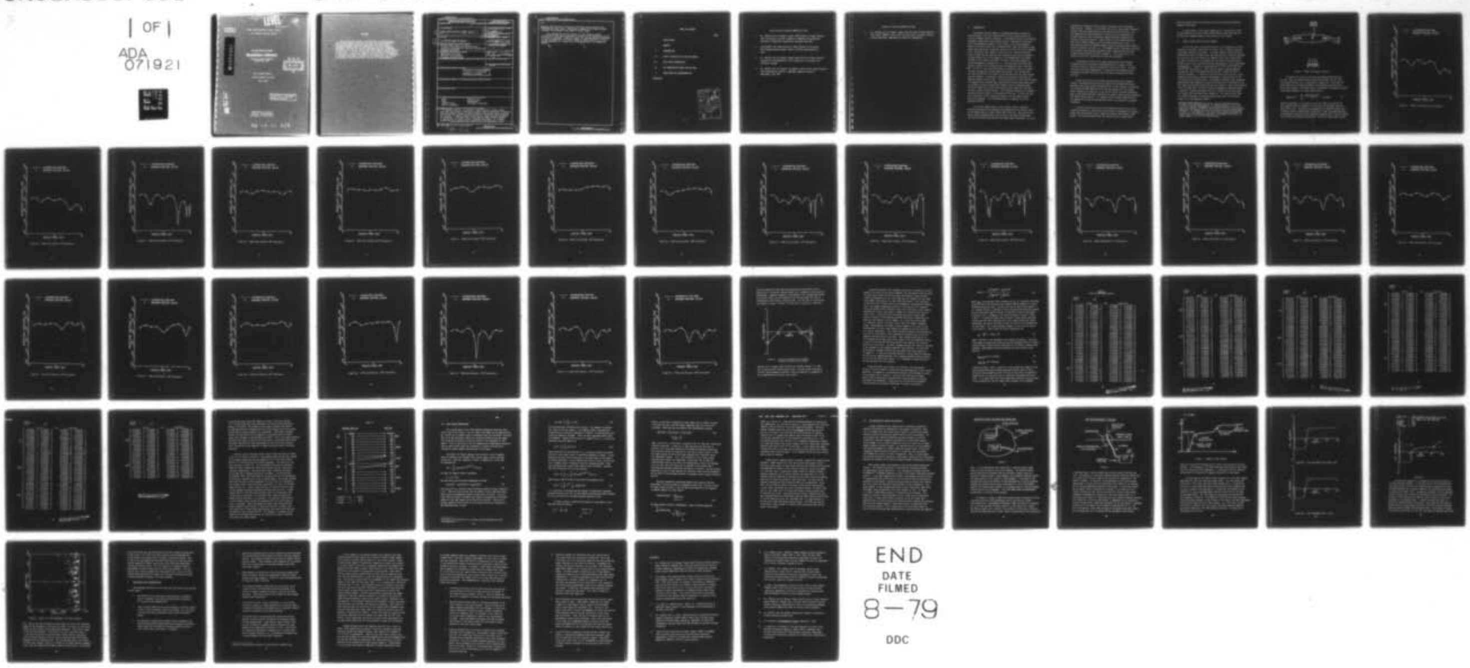

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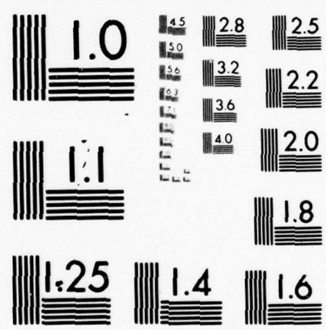

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RADAR IDENTIFICATION OF NAVAL VESSELS

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Columbus, Ohio 43212

FINAL REPORT 784558-1
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Department of the Navy
Office of Naval Research
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Research progress on a method of identification of naval vessels from radar data based on substructure complex natural resonances is reported. Discrete multiple-frequency scattering data on two vessels (one battleship, one cruiser) for aspects bracketing the bow-on, abeam and stern-on aspects are presented. From these data a relatively new type response waveform is synthesized and complex natural resonances extracted. It is demonstrated that the suggested quasi-invariance of the resonances is true

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and that identification is also quasi-invariant to the aspect of the interrogating radar signal. Accordingly, probability of identification estimates are extended to new ranges of vessel aspect.

Also reported are initial results of a new system to obtain characteristic time domain waveforms of targets via an encapsulated source and receiver technique. Promising results are obtained when this technique is used in conjunction with Prony's method to obtain the poles of a conducting hemisphere on a ground plane (the odd TM poles of a conducting sphere).

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Publications on Contract N00014-76-C-1079

1. D.L. Moffatt and C.M. Rhoads, "Radar Identification of Naval Vessels," 1978 International IEEE/AP-S Symposium, USNC/URSI Spring Meeting, University of Maryland, College Park, Maryland, May 1978.

2. C.M. Rhoads, "The Identification of Naval Vessels Via an Active, Multifrequency Radar System," Thesis, The Ohio State University 1978.

3. D.L. Moffatt and C.M. Rhoads, "Radar Identification of Naval Vessels," accepted as correspondence by IEEE Transactions on Aerospace and Electronic Systems.

4. D.L. Moffatt and C.M. Rhoads, "An Undate on Naval Vessel Identification," 1979 International IEEE/AP-S, USNC/URSI Symposium, Seattle, Washington, June 1979.

Reports on Contract N00014-76-C-1079

1. D.L. Moffatt and C.M. Rhoads, "Radar Identification of Naval Vessels," Final Report 784558-1, April 1979, The Ohio State University ElectroScience Laboratory, Department of Electrical Engineering.

I. INTRODUCTION

The purpose of this report is to update previously reported research progress [1] on the identification of naval vessels using substructure complex natural resonances. A multitude of details on a harmonic frequency reflectivity range, complex natural resonances of structures, valid electromagnetic models of naval vessels, valid electromagnetic models of the sea surface and a "matched-filter" type interrogating radar signal have been given in previous reports [1,2] and will not be repeated here. One should note, however, that the use of a conducting ground plane to model the sea restricts the frequencies that can be simulated to some highest full scale frequency in the neighborhood of 25.0 MHz. The model scale factors used (500:1 or 700:1) allow good geometrical and electromagnetic simulation but it is not possible with the present system to obtain valid scattering data at frequencies higher than 25.0 MHz. In fact, if the sea surface must be considered rough it is doubtful that any physical ship-sea model can be used. This problem does not limit the feasibility studies of the present effort but does dictate that our methods, if successful, cannot be conveniently tested at frequencies greater than 25.0 MHz. The present feeling is that identification at frequencies much greater than those presently being tested would have to be based on certain substructure complex natural resonances whose extraction would be seriously affected by the sea state and wind state as well as other variable factors. The resonance frequencies of interest are those with the vessel in the presence of the sea. In this case the quasi-invariance of the resonances might be lost and identification seriously distorted. The interested reader is referred to [1] for pertinent details.

It has been demonstrated [1] that complex natural resonances extracted (matched filter waveform) from measured data at bow-on, stern-on and abeam aspects of naval vessels were different. The stern-on and bow-on aspect resonances were similar but not the same and both were distinctly different than those of the abeam aspect resonances. At first

examination it appeared that the aspect invariance of the resonances does not hold. However, it was pointed out that at these widely different aspects different substructures of the vessels could be excited. Thus for geometrically complicated naval vessels all of the resonances are actually there but only the observed subsets of these resonances are excited at the given aspects. Similar effects can be demonstrated for even such a simple target as a finite length conducting cylinder. It was postulated that the observed complex natural resonances would actually prove to be quasi-invariant, i.e., the complex natural resonances extracted at the bow-on aspect would also permit vessel identification for some range of aspects around the bow-on geometry. A principal goal of our research during this interim was to prove this postulate.

In the next section of this report measured multiple frequency scattering data are presented (representatively) for aspects in the vicinity of bow-on, stern-on and abeam for two naval vessels. The next section of the report demonstrates a clustering of the complex natural resonances extracted from these data with those resonances previously obtained.

In the next section of the report entitled "Data Record Combinations", the problem of extracting an identification-usable difference equation from target records corresponding to various aspects is discussed. It is shown that the method used for the data analysis in the studies, Prony's method and clustering, is but one of several different approaches some of which may offer more convenient and compact identification parameters. The identification results, i.e, probabilities of target identification are updated to include the new measured results and resultant "clustered" resonances.

In the next section results on an encapsulated source and receiver system are presented. Using a worst case target (a hemisphere on a ground plane) data are obtained using a simple time domain reflectometry (TDR) system. The poles extracted from this data are found to agree quite

well with those obtained by Stratton [11] for the perfectly-conducting sphere in free space.

A final section of the report summarizes our conclusions to date on the feasibility of naval vessel identification using radar data and outlines our intended research tasks during the next interim.

II. ASPECT CLUSTER DATA OF TWO SHIP MODELS

To test the aspect invariance postulate it was necessary to extract resonances from model target data for several sets of aspects clustered about major aspects of the models. The major aspects selected were bow, broadside and stern incidence (only one broadside set of data was obtained for each ship since the targets are symmetric about their centerlines). An angular increment of five degrees was selected yielding three unambiguous views in each direction from the major aspects. Thus, each target was measured at 11 aspects corresponding to $0^{0}(5^{0})10^{0}$, $80^{0}(5^{0})100^{0}$ and $170^{0}(5^{0})180^{0}$ (see Figure 1). Note that the angle is degrees measured from bow-on, thus 0^{0} corresponds to bow-on, 90^{0} to abeam and 180^{0} to stern-on incidence. It should also be noted that since a bistatic radar system was used, bow-on incidence corresponds to the centerline of the ship bisecting the antenna angle. The harmonic frequency radar system and ground plane range geometry are more fully explained in references [1,2]. The range used to obtain these data was very similar to that used previously except for some minor variations including placement of absorber panels. In addition, changes were made in the R.F. system such that more power was coupled into the higher order harmonics*. For these reasons there are slight differences in the data reported here and in the previous study [1] for corresponding aspects.

*The major modification was the use of a Varian ortho-mode modulator in place of the balanced modulator at X-band (harmonics 7, 8, 9, and 10 of the 1.085 GHz fundamental). The balanced modulator was used to modulate the signals at the 20.2 MHz reference from the network analyzer (Reference [2], Appendix A) but did not have the necessary bandwidth to cover all four harmonics. The use of the orthomode modulator has significantly increased the output power at harmonics 7, 8 and 9 although harmonic 10 is still relatively weak.

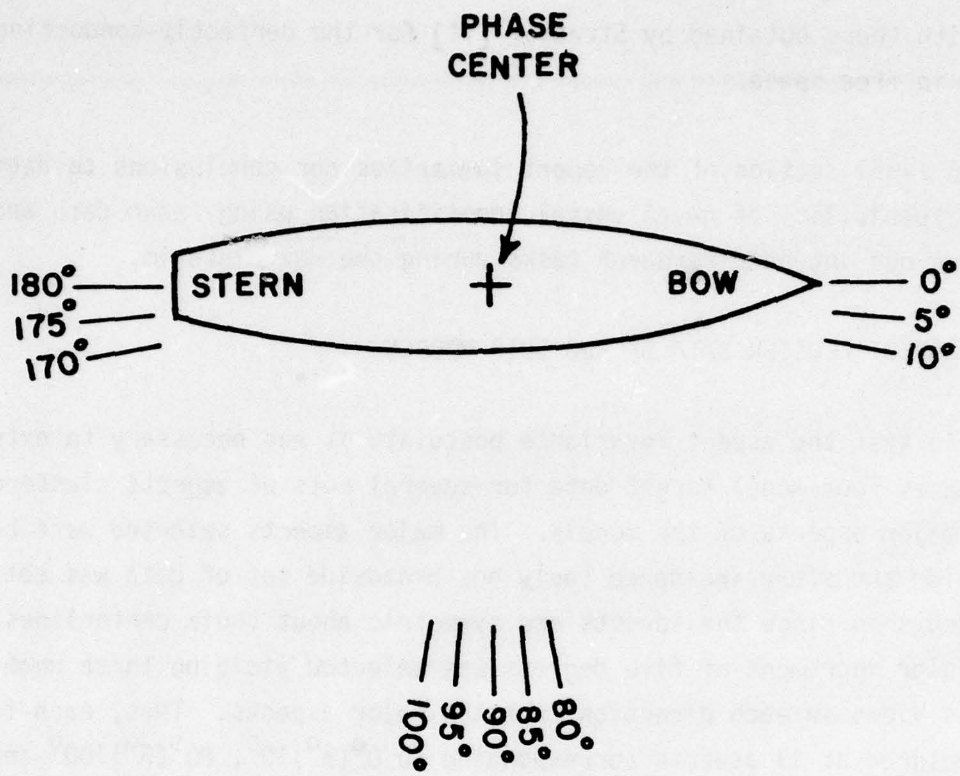

Figure 1. Radar interrogation aspects.

In Figures 2a-k and 3a-k are given the measured amplitude data for the 1:500 scale model Sverdlov (a Russian Cruiser) and the 1:700 scale model Missouri (a U.S. Battleship), respectively. Also shown on those figures are interpolated spectra (see Reference [1]) which are not used at present. From these data at the harmonic frequencies, matched-filter type responses [1,2] were constructed as

$$f_{mf}(\theta,\phi,\hat{p},t) = \sum_{n=1}^{10} \frac{|G(\theta,\phi,\hat{p},jn\omega_0)|^2}{n^2} \cos(n\omega_0 t), \qquad (1)$$

where $G(\theta,\phi,\hat{p},jn\omega_0)$ is the square root of the radar cross section of the target at the n-th harmonic as a function of view angle (θ,ϕ) and polarization $(\hat{p})$. The principle advantage of this waveform (whose justification is given in References [1] and [2]) is that only amplitude data are required in contrast to the ramp-type responses used in earlier studies which require both amplitude and phase. This use of phase data dictates

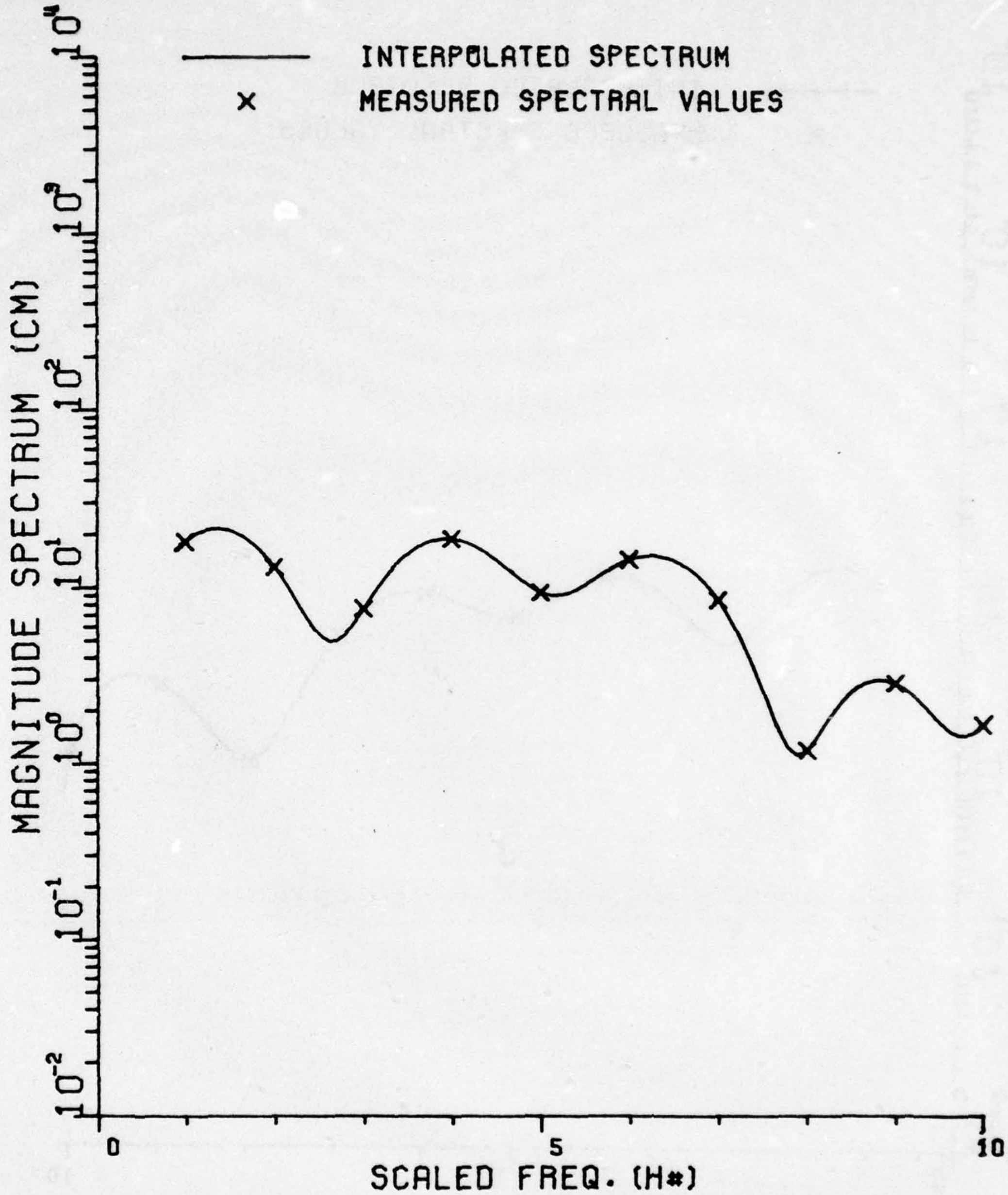

Figure 2a. 1/500 scale Sverdlov, 0^0 from bow-on.

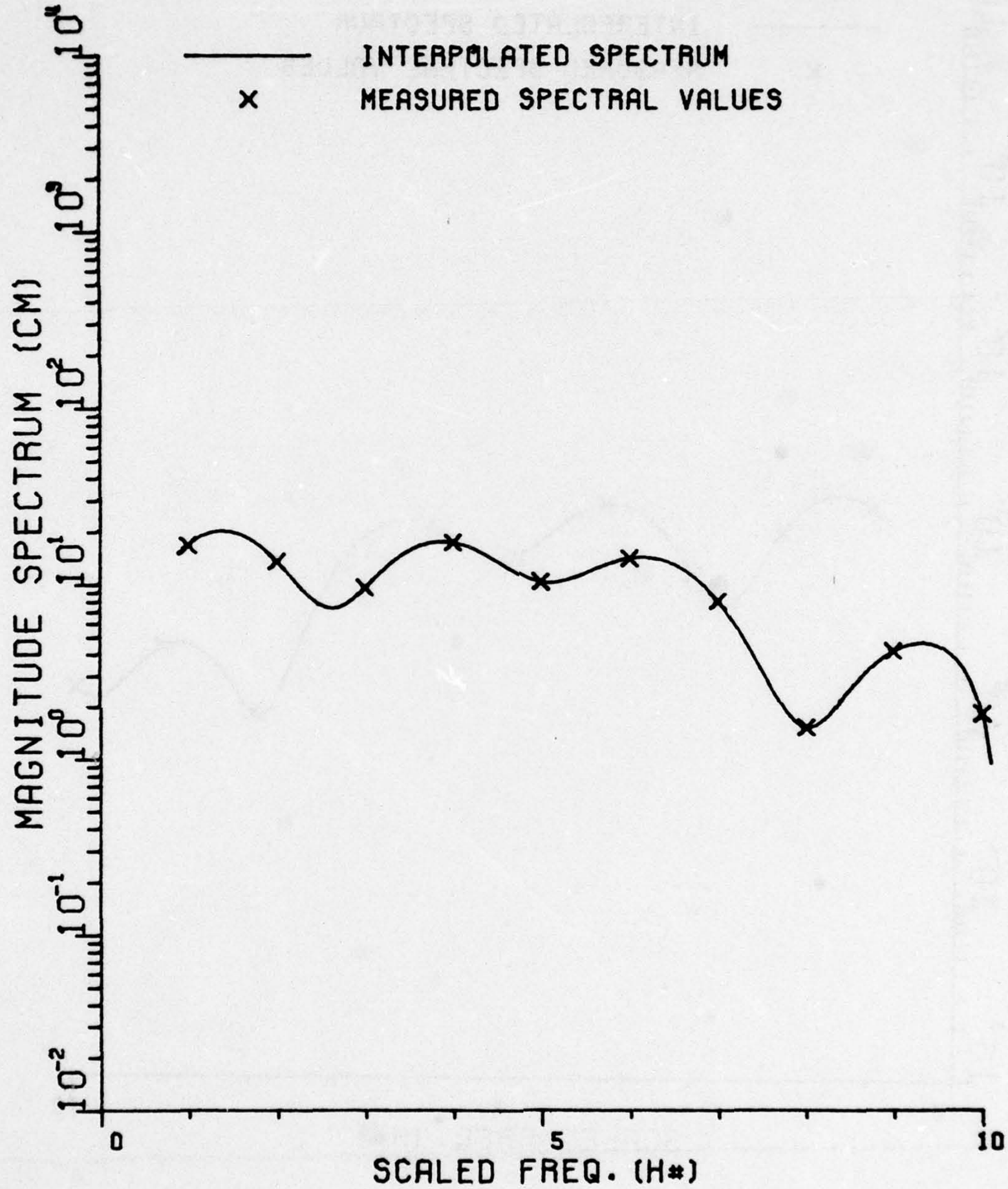

Figure 2b. 1/500 scale Sverdlov, 5^{0} from bow-on.

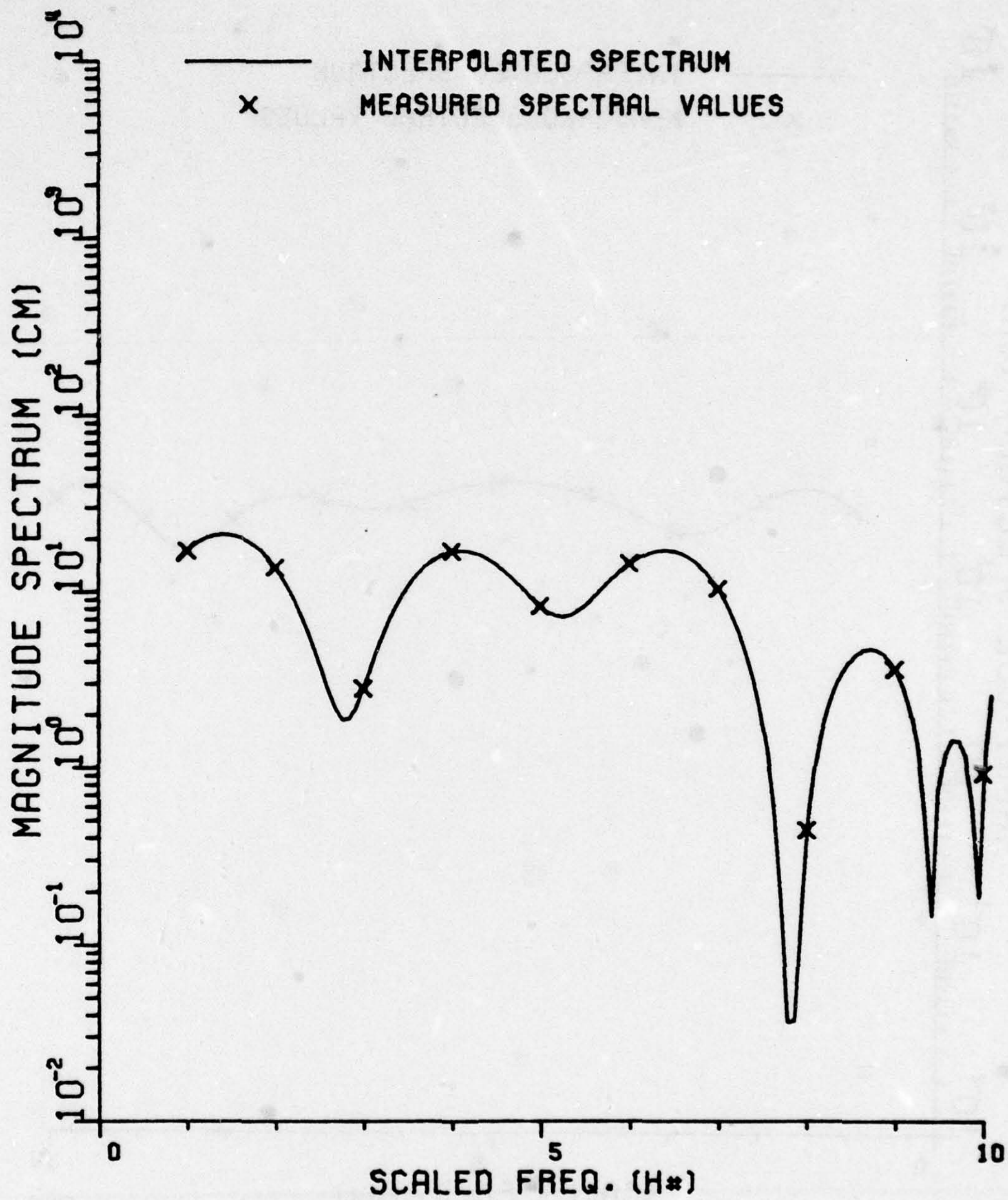

Figure 2c. 1/500 scale Sverdlov, 10^{o} from bow-on.

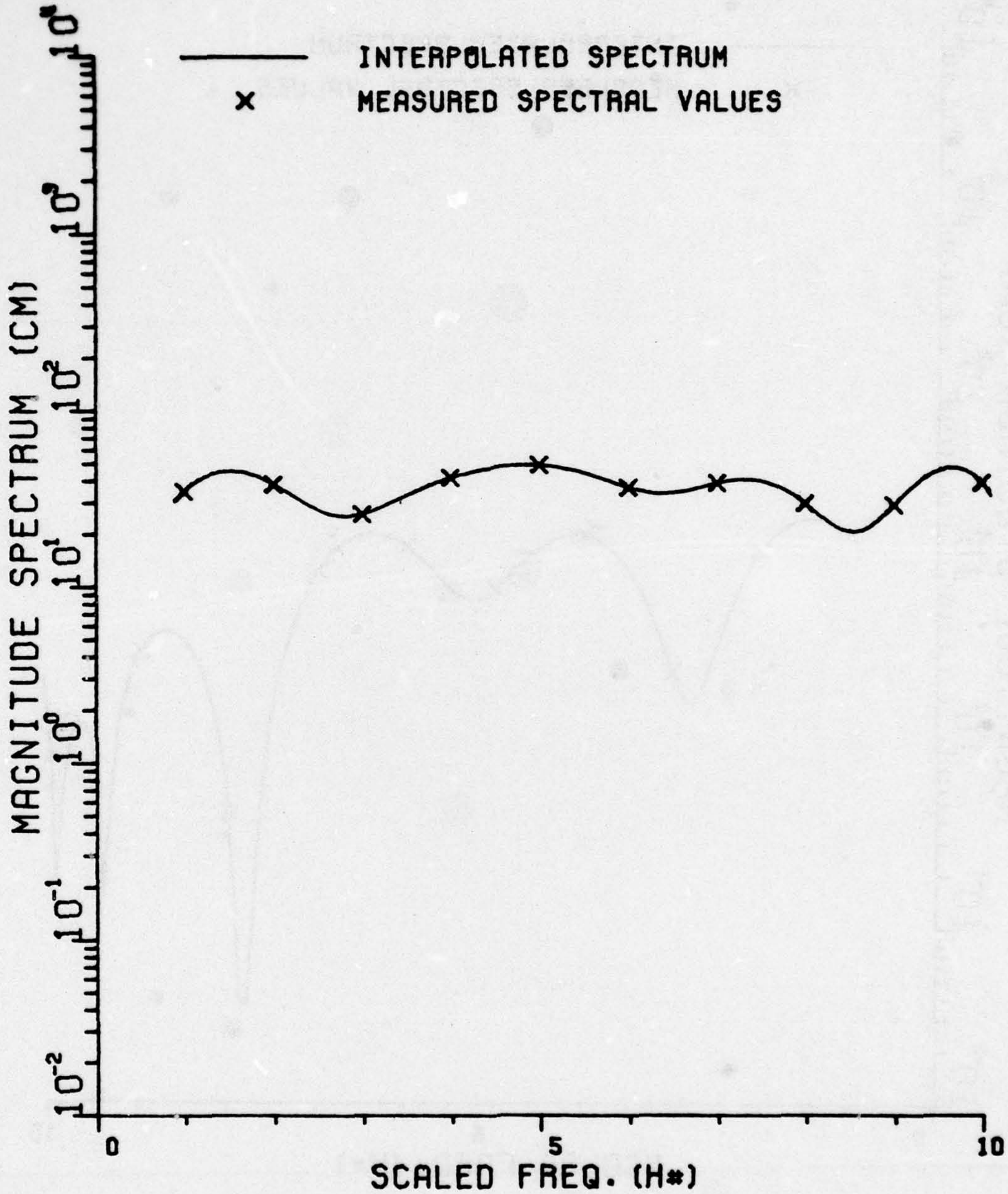

Figure 2d. 1/500 scale Sverdlov, 80° from bow-on.

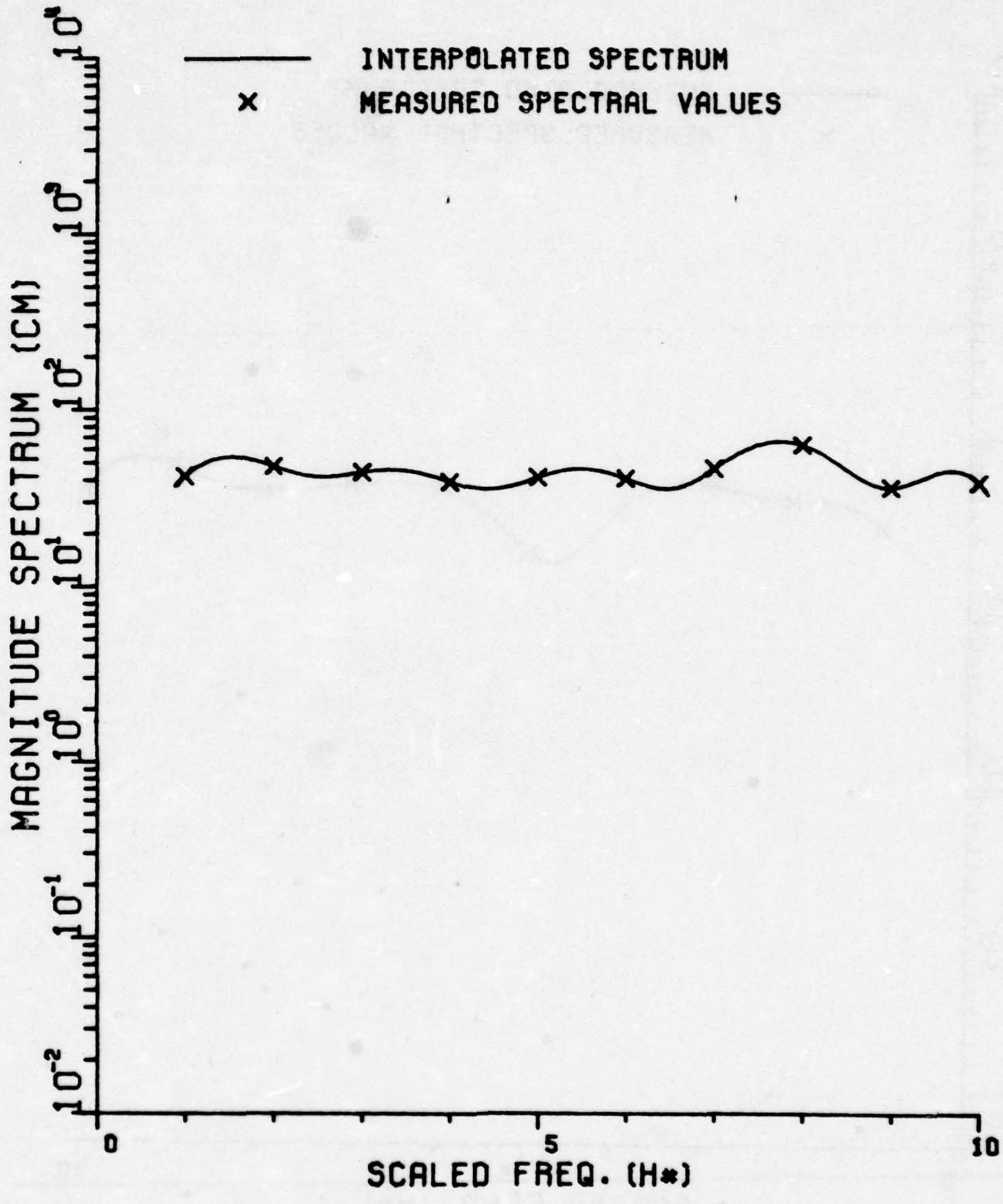

Figure 2e. 1/500 scale Sverdlov, 85^{0} from bow-on.

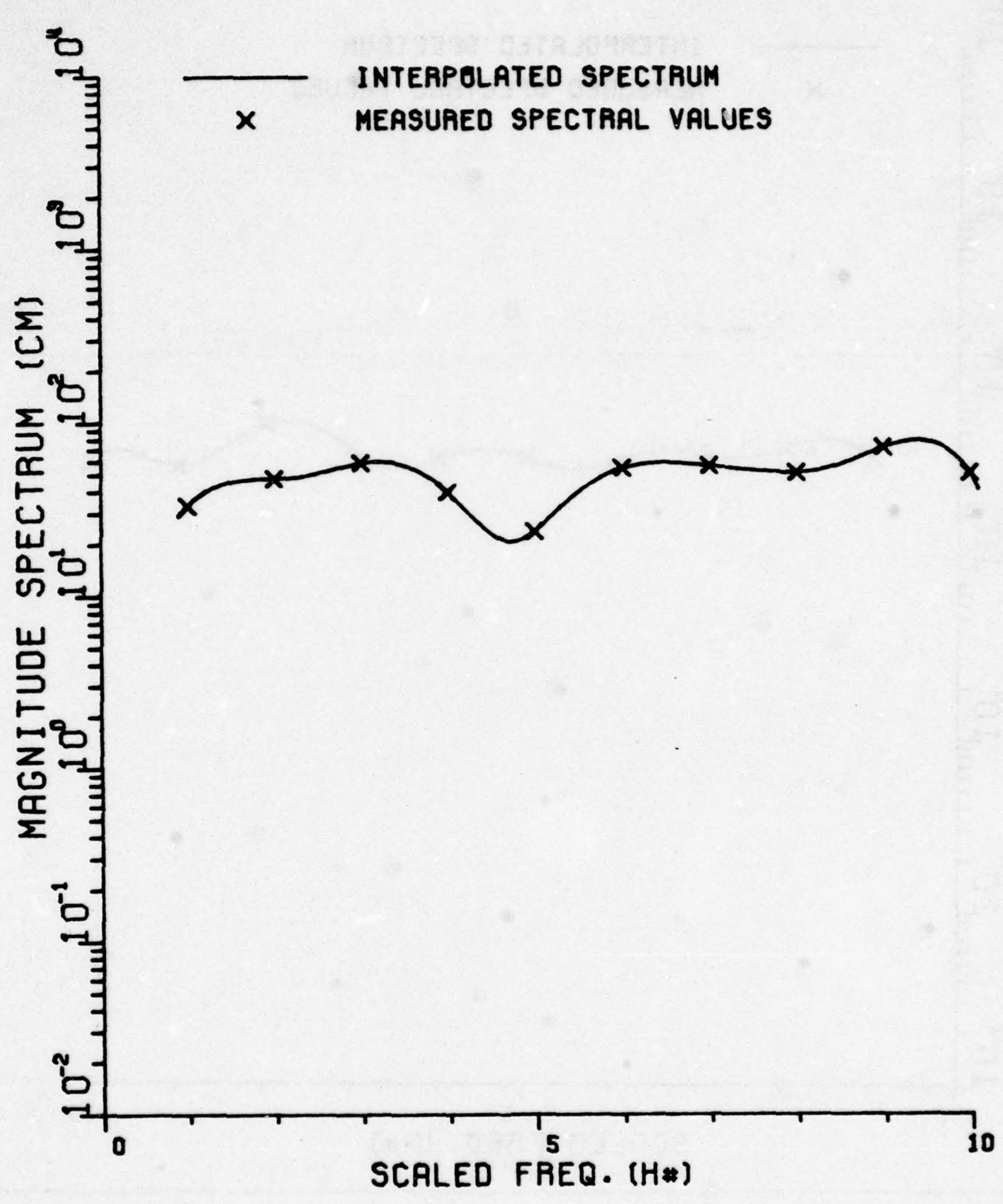

Figure 2f. 1/500 scale Sverdlov, 90^{o} from bow-on.

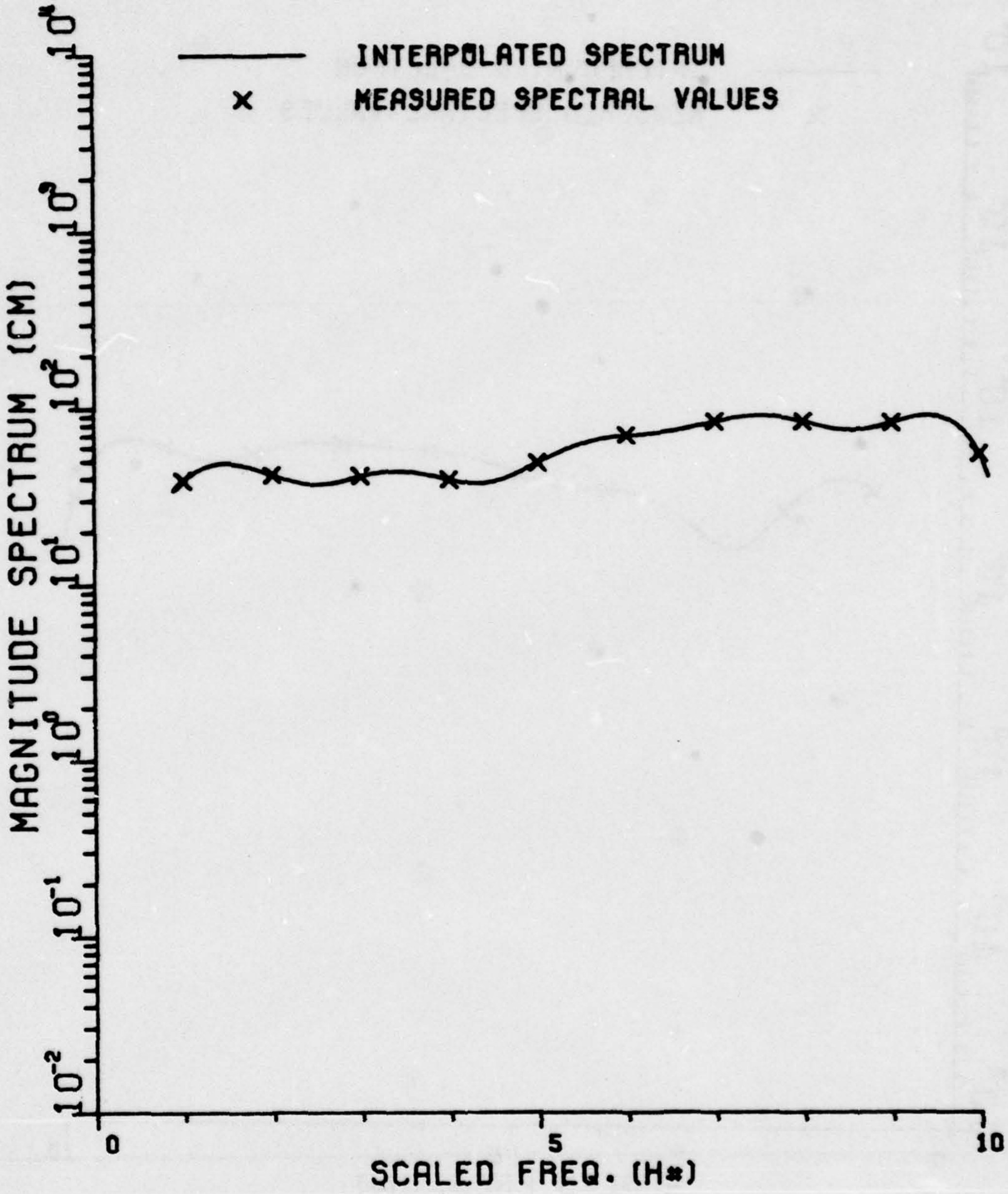

Figure 2g. 1/500 scale Sverdlov, 95^0 from bow-on.

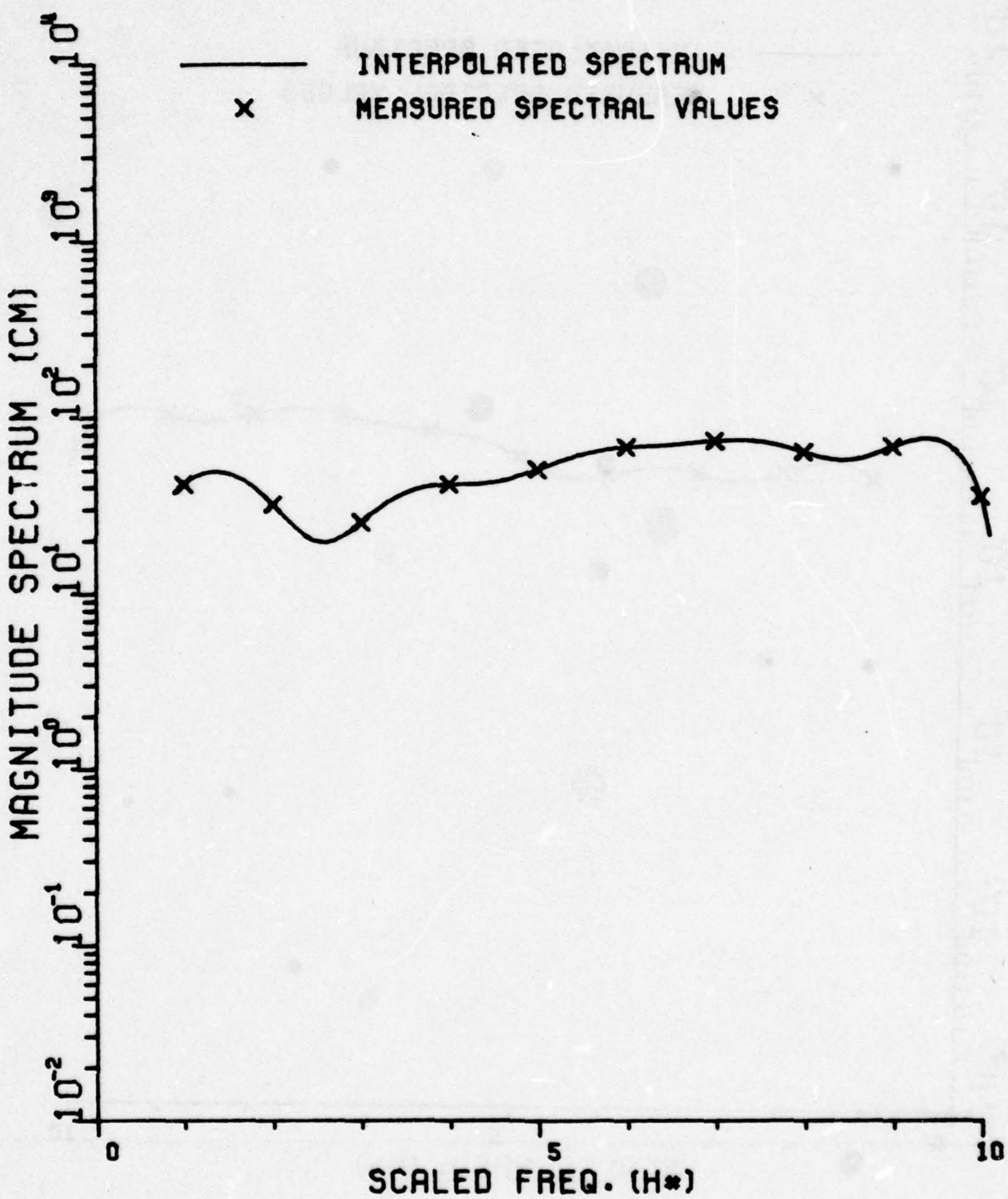

Figure 2h. 1/500 scale Sverdlov, 100° from bow-on.

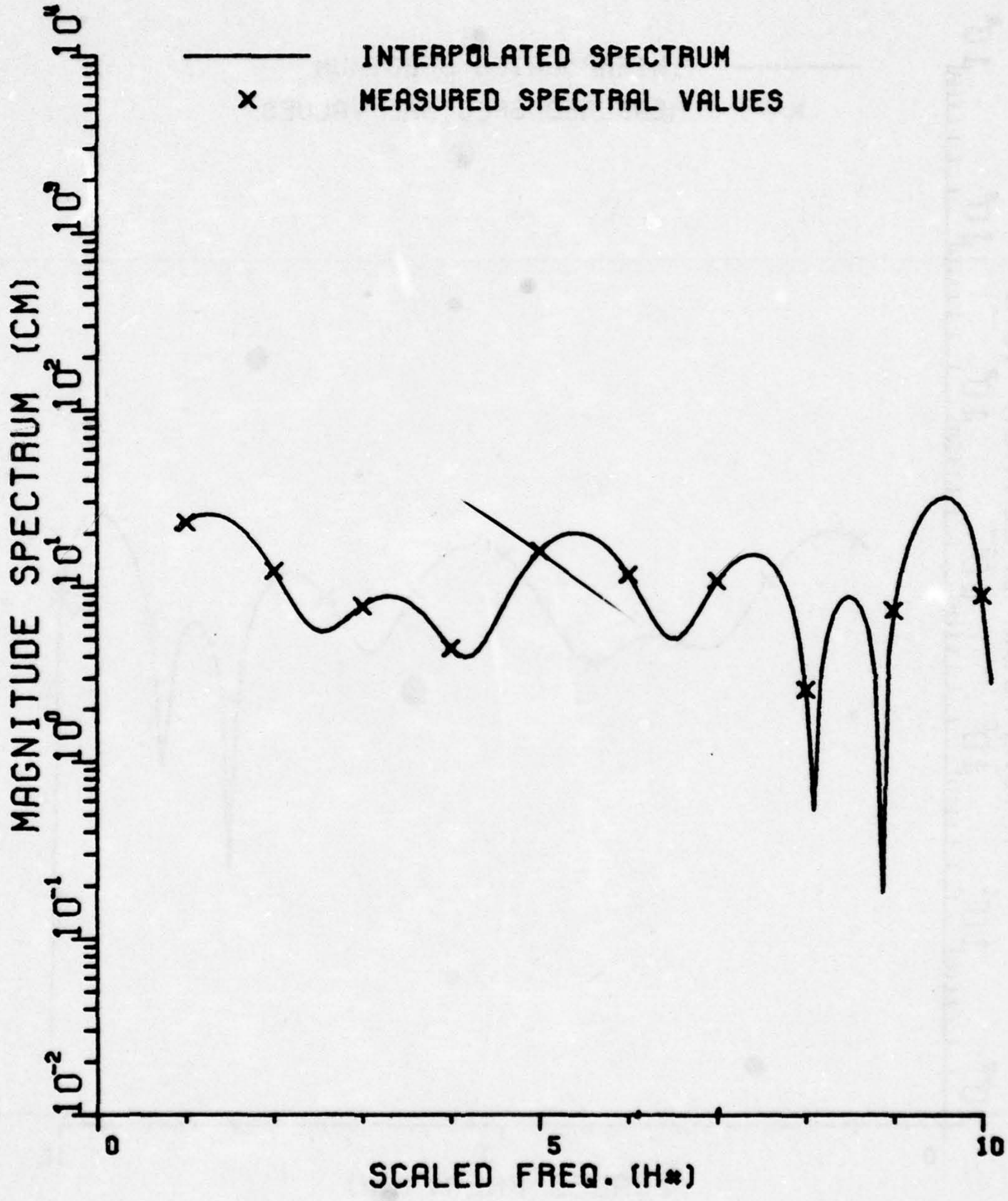

Figure 2i. 1/500 scale Sverdlov, 170° from bow-on.

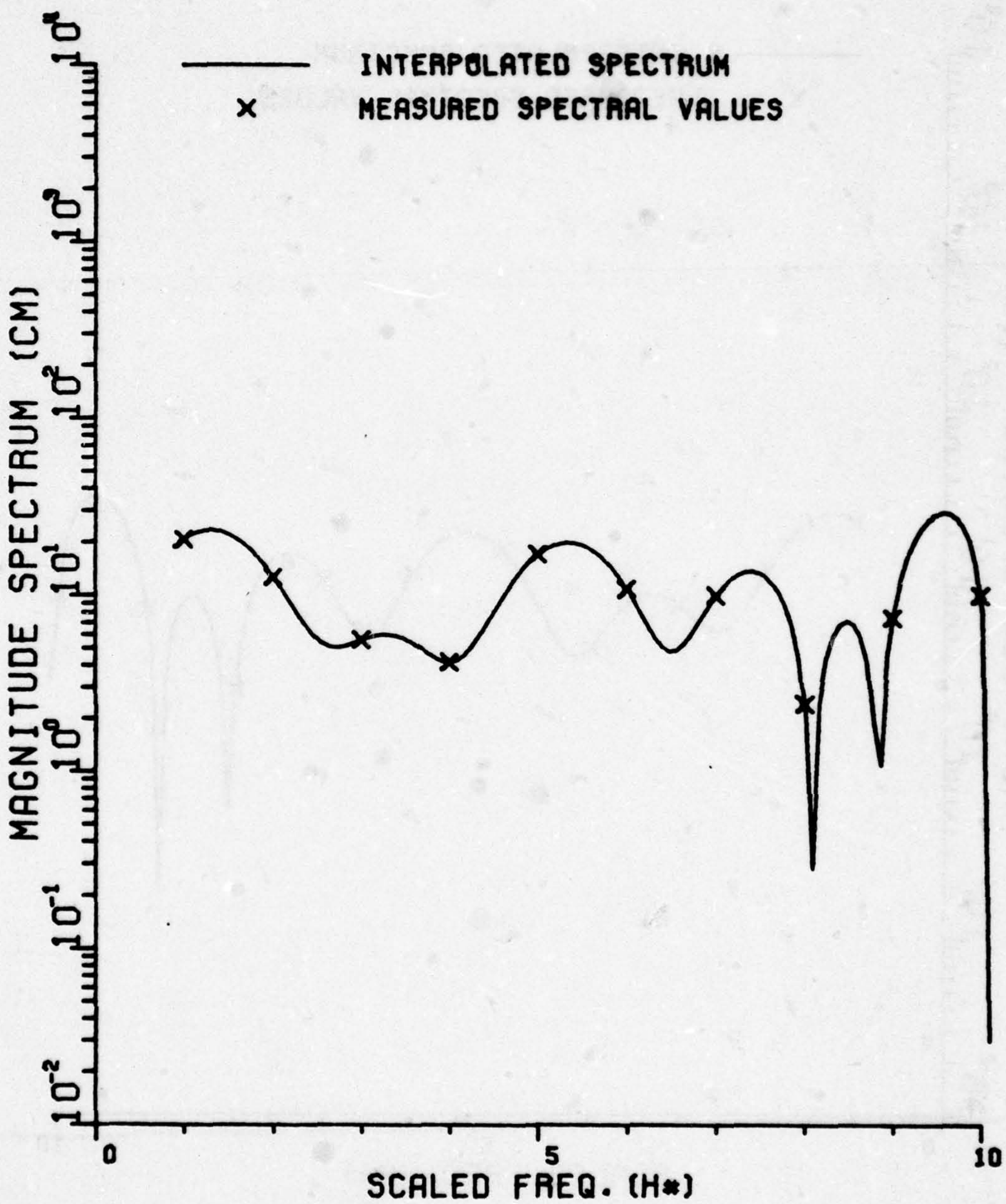

Figure 2j. 1/500 scale Sverdlov, 175° from bow-on.

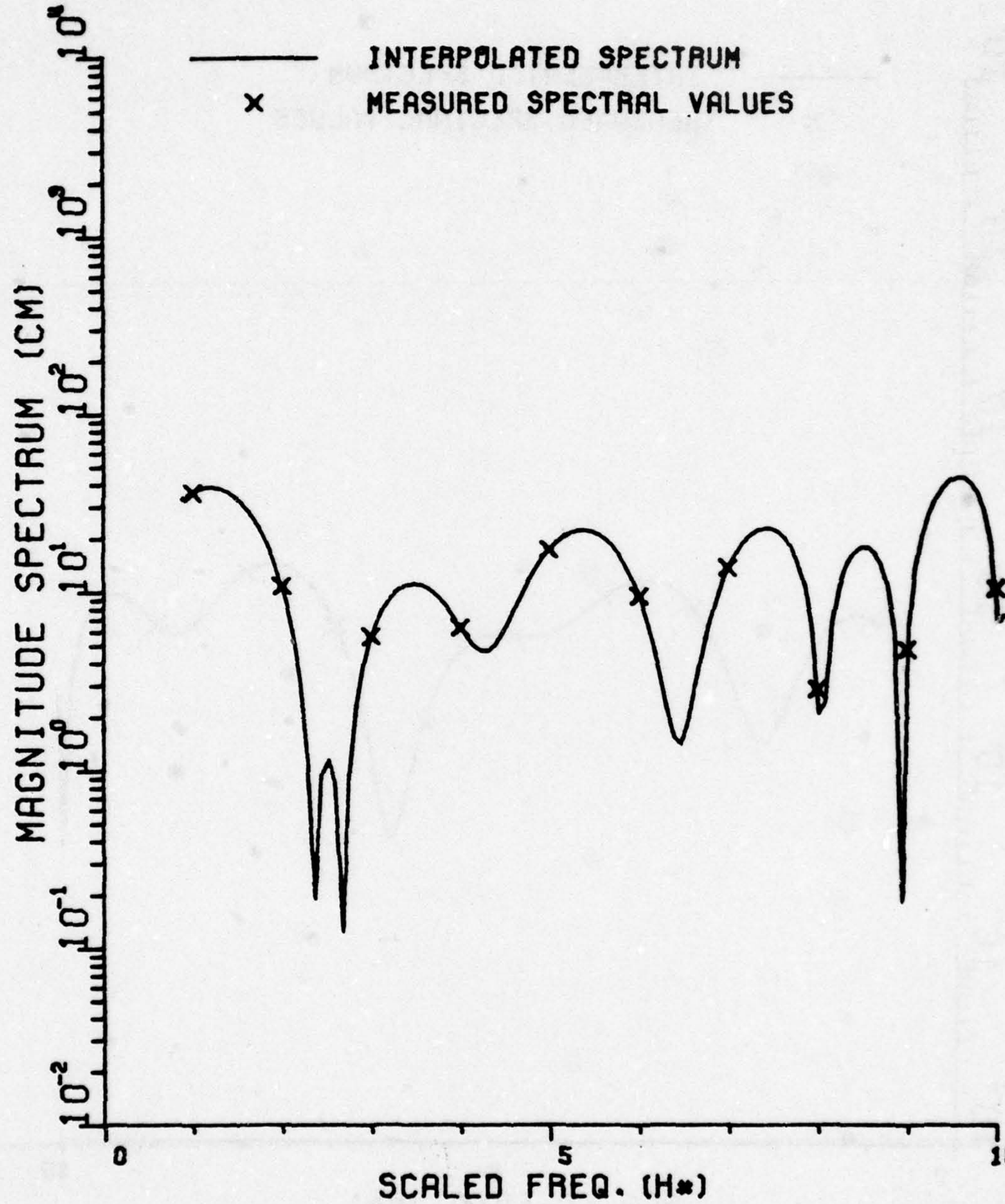

Figure 2k. 1/500 scale Sverdlov, 180° from bow-on.

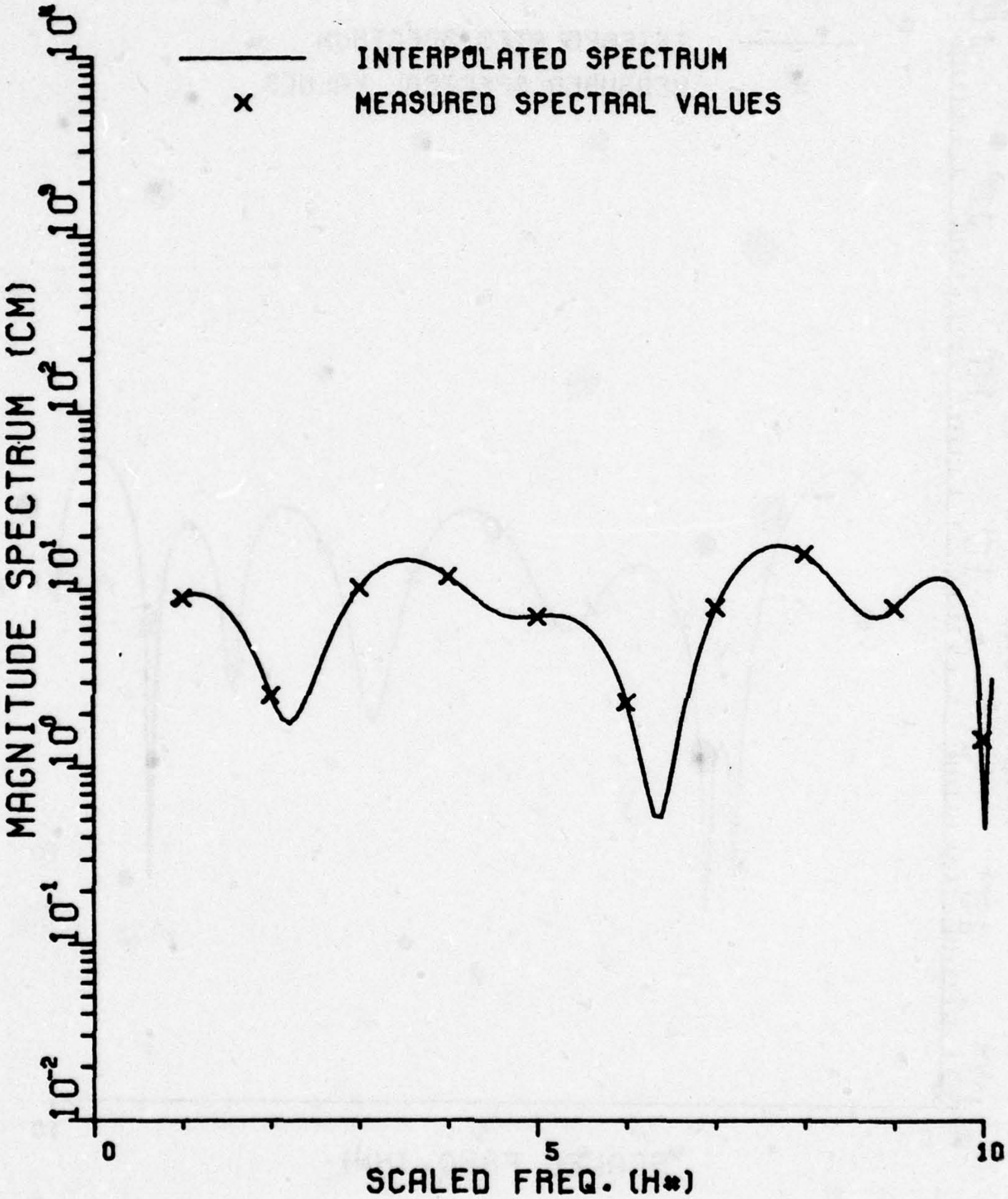

Figure 3a. 1/700 scale Missouri, 0^{o} from bow-on.

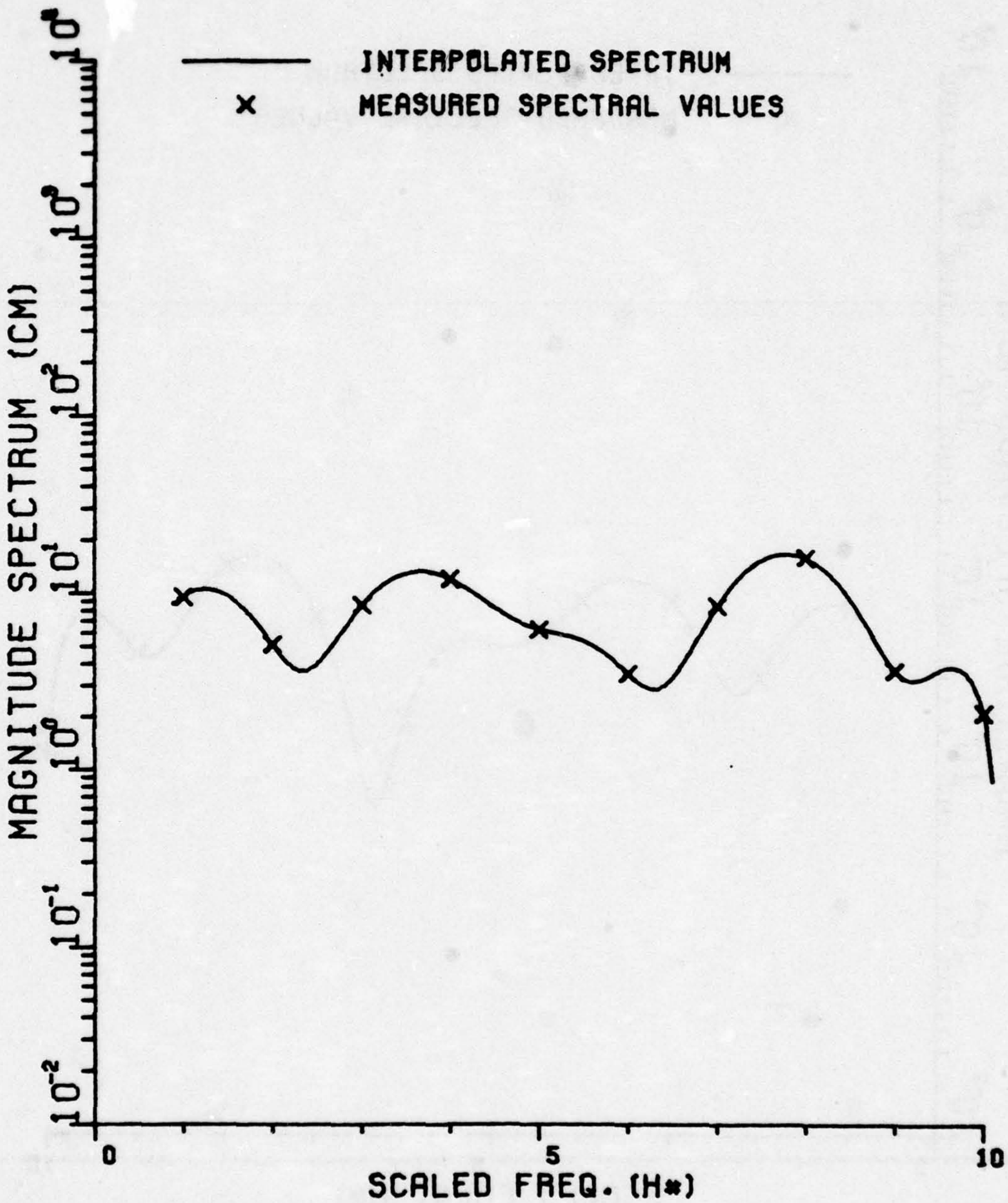

Figure 3b. 1/700 scale Missouri, 5^{0} from bow-on.

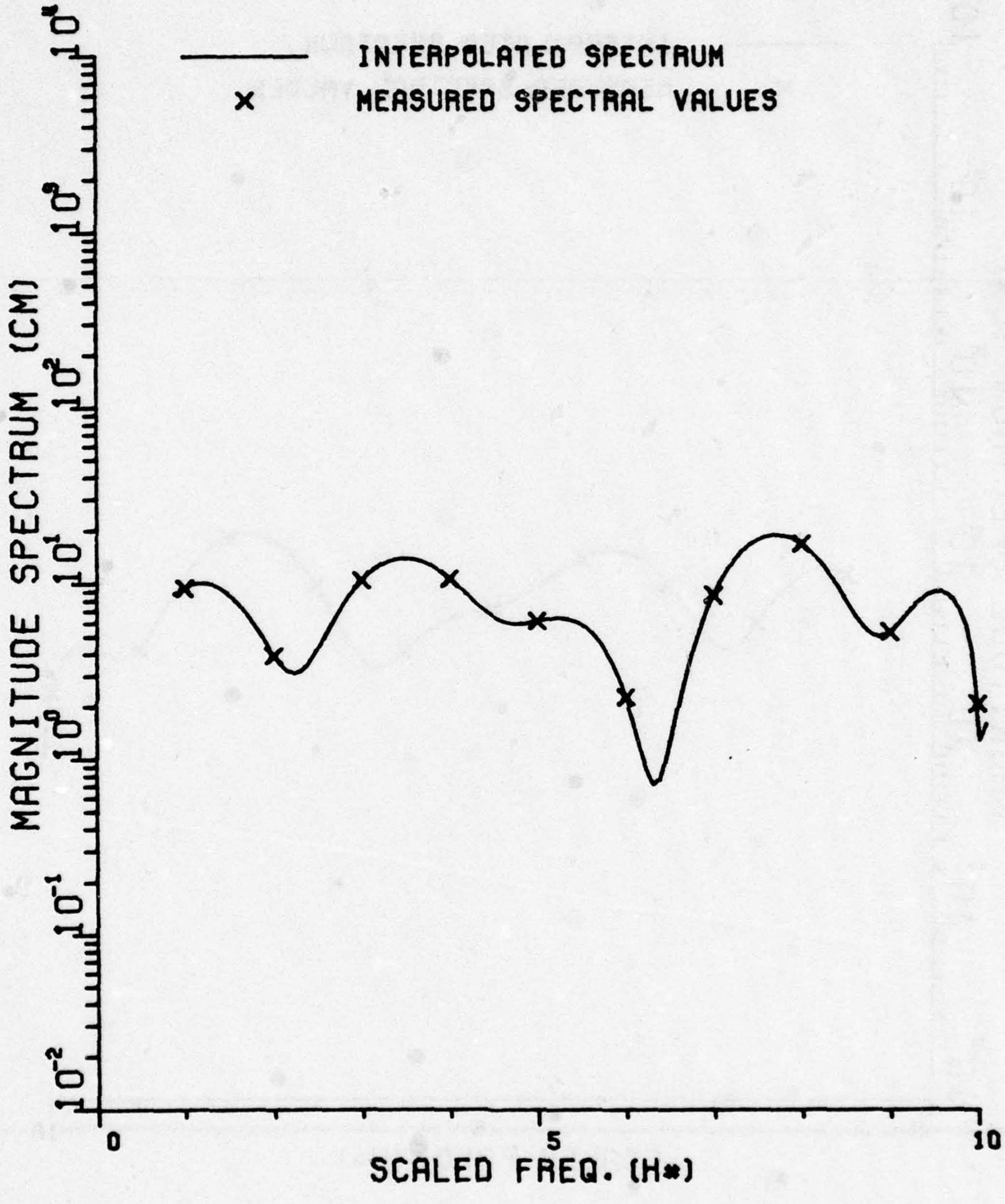

Figure 3c. 1/700 scale Missouri, 10^{0} from bow-on.

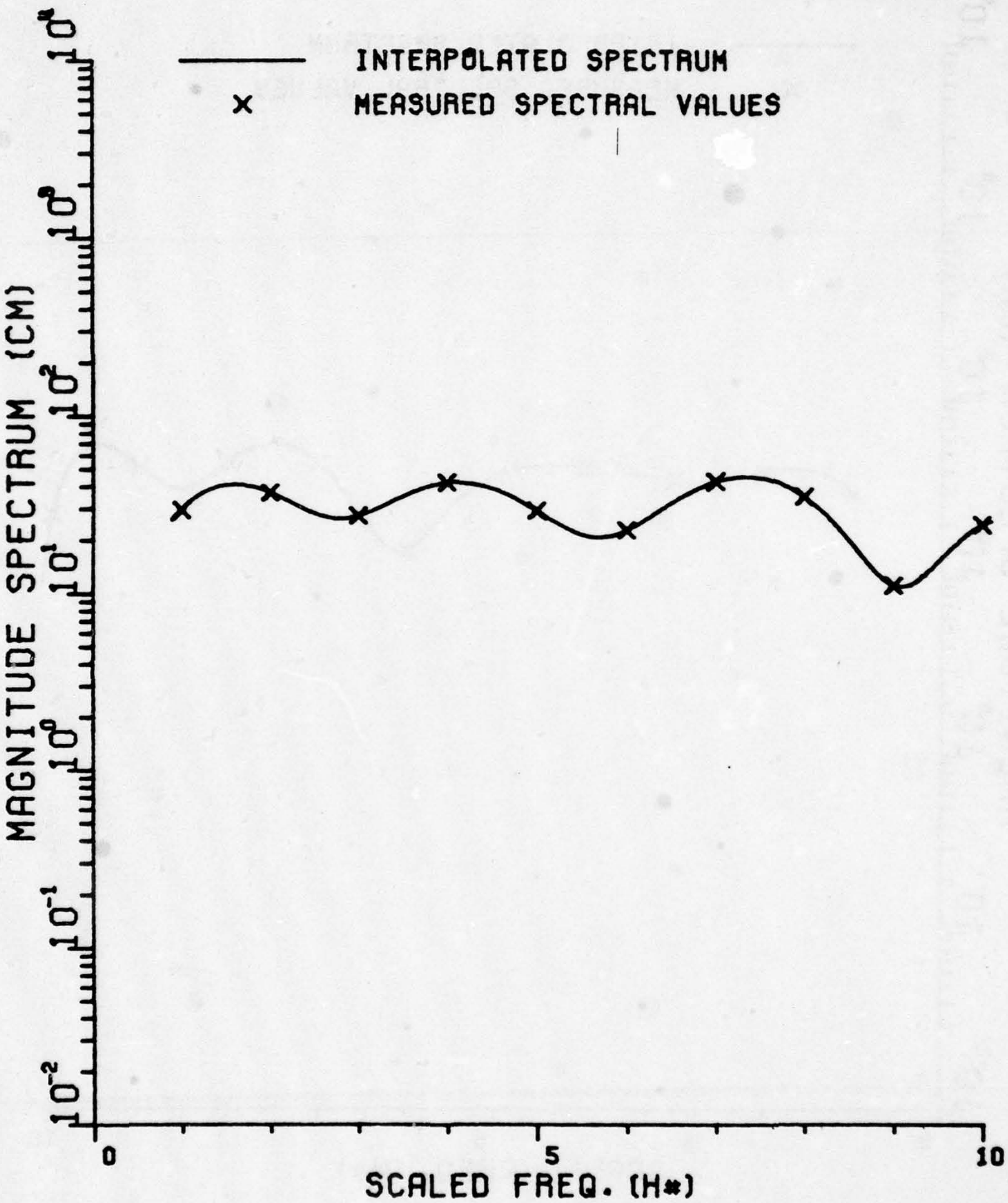

Figure 3d. 1/700 scale Missouri, 80^{0} from bow-on.

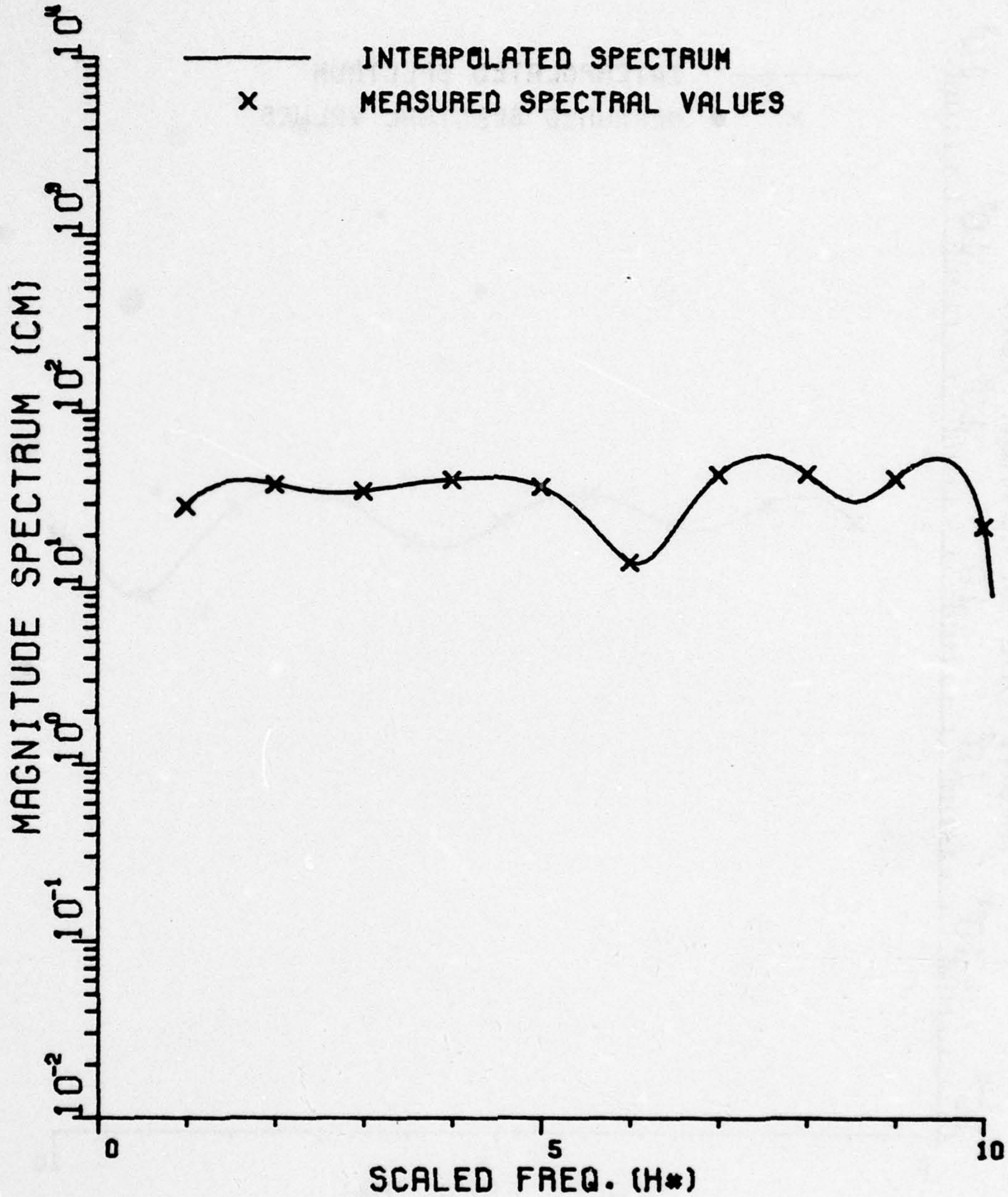

Figure 3e. 1/700 scale Missouri, 85^0 from bow-on.

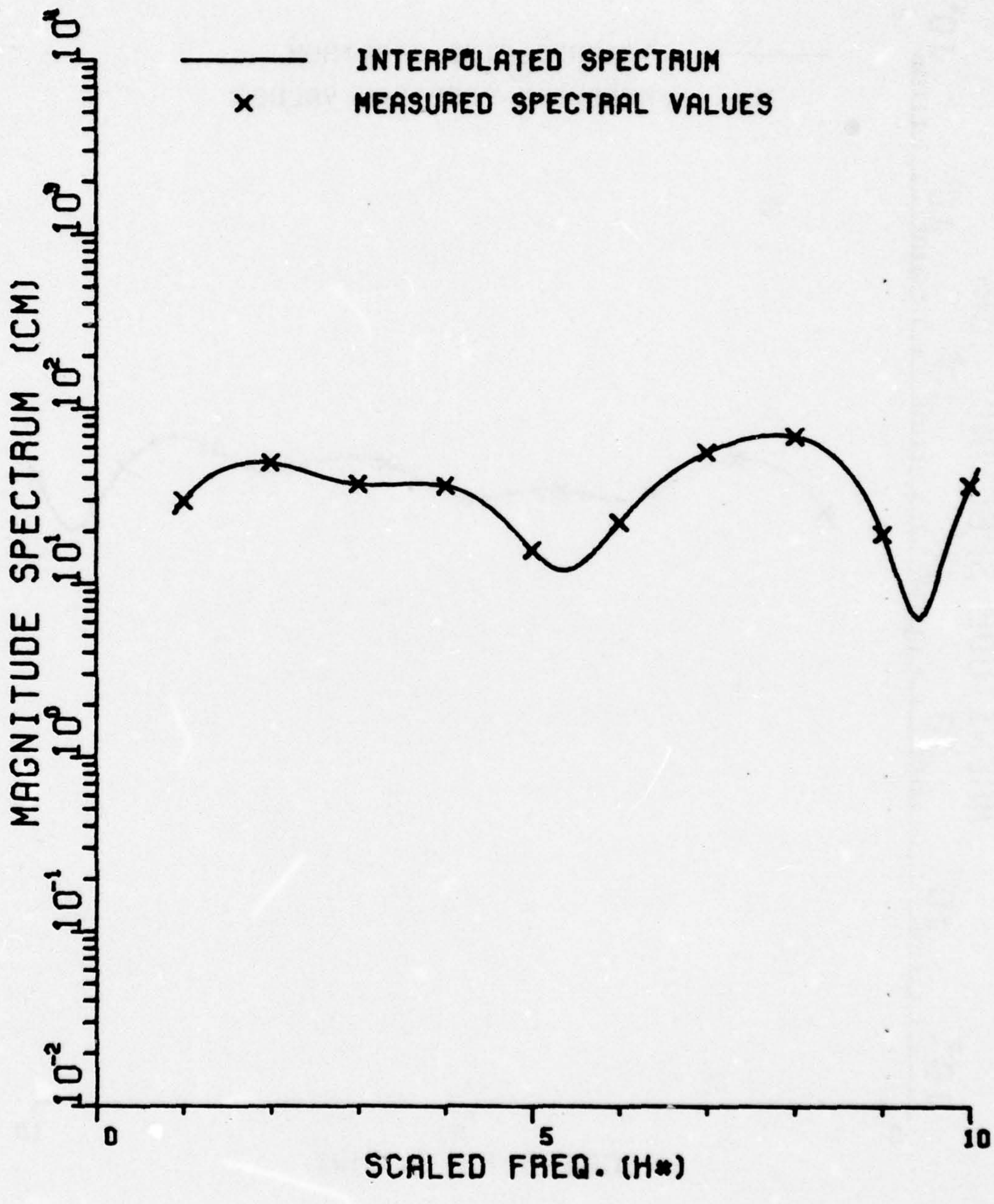

Figure 3f. 1/700 scale Missouri, 90^{0} from bow-on.

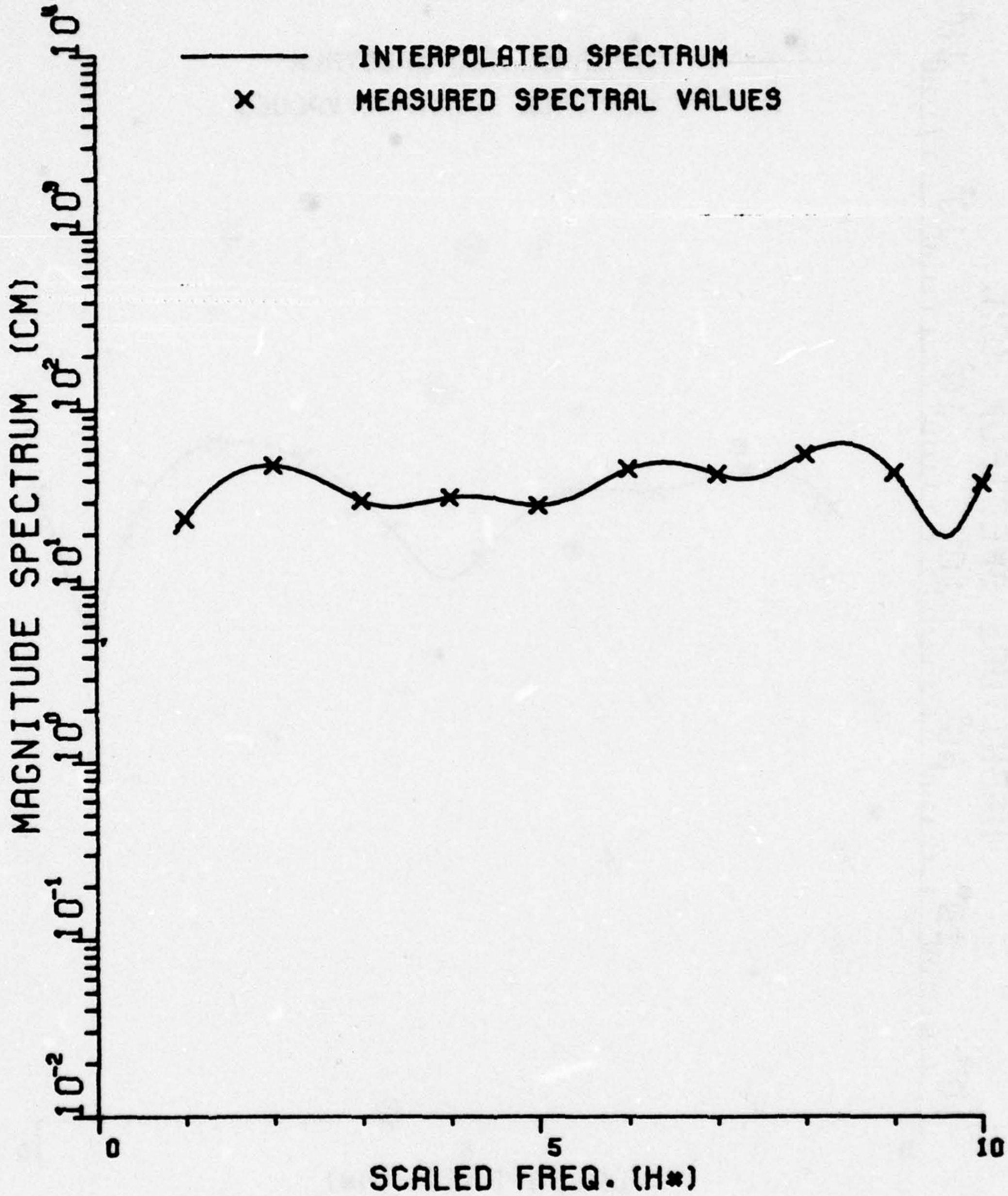

Figure 3g. 1/700 scale Missouri, 95^{o} from bow-on.

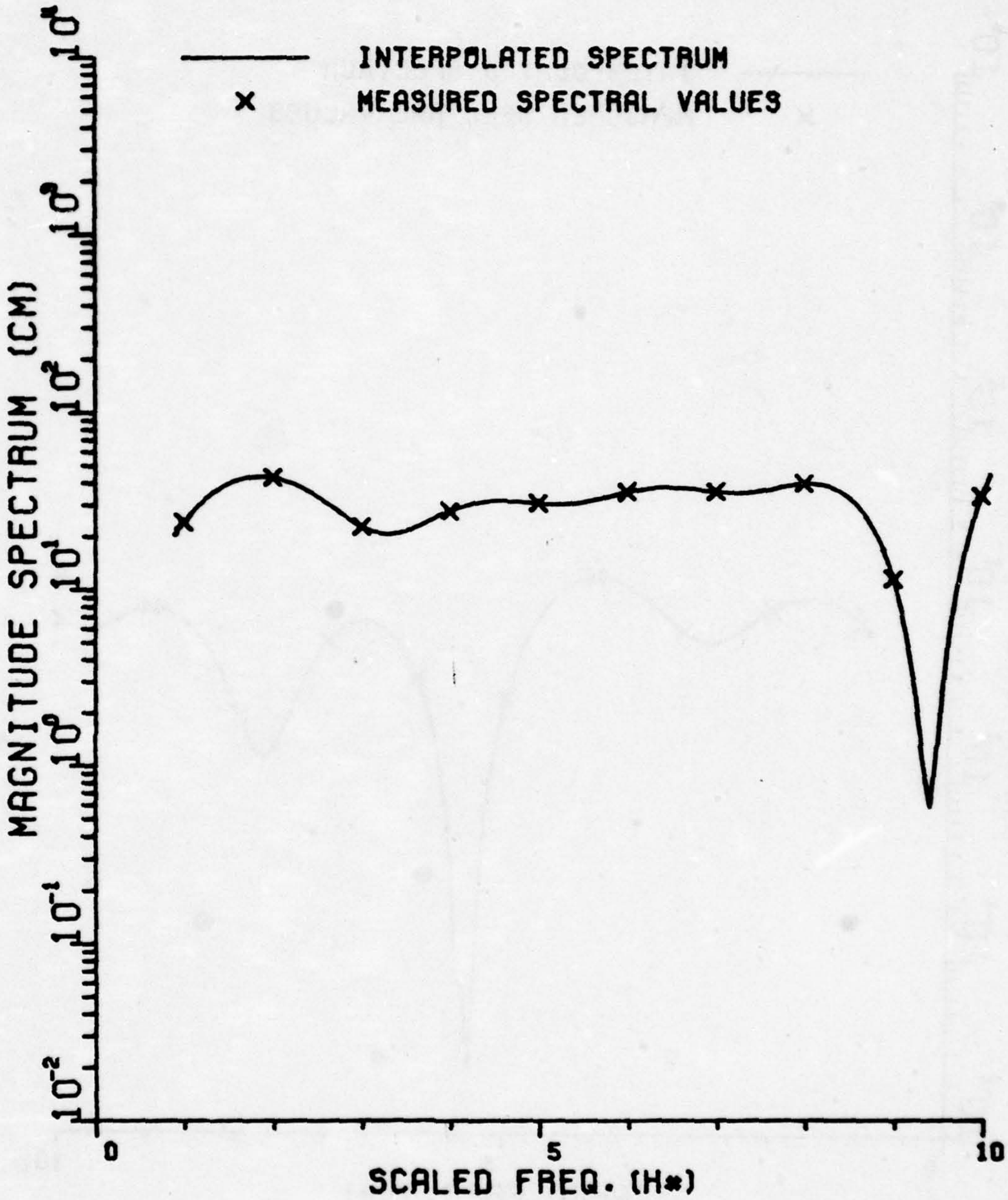

Figure 3h. 1/700 scale Missouri, 100^{0} from bow-on.

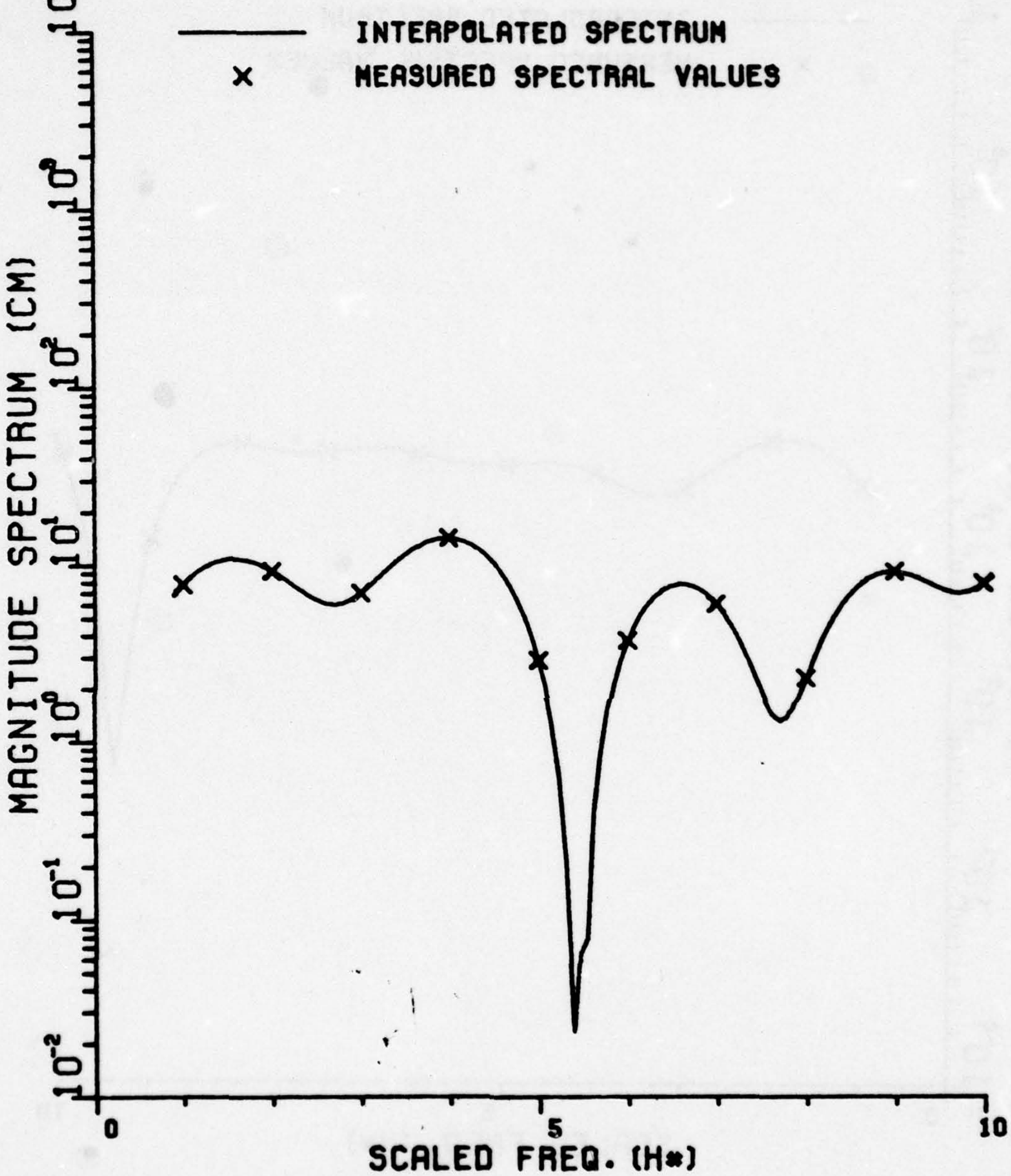

Figure 3i. 1/700 scale Missouri, 170^{0} from bow-on.

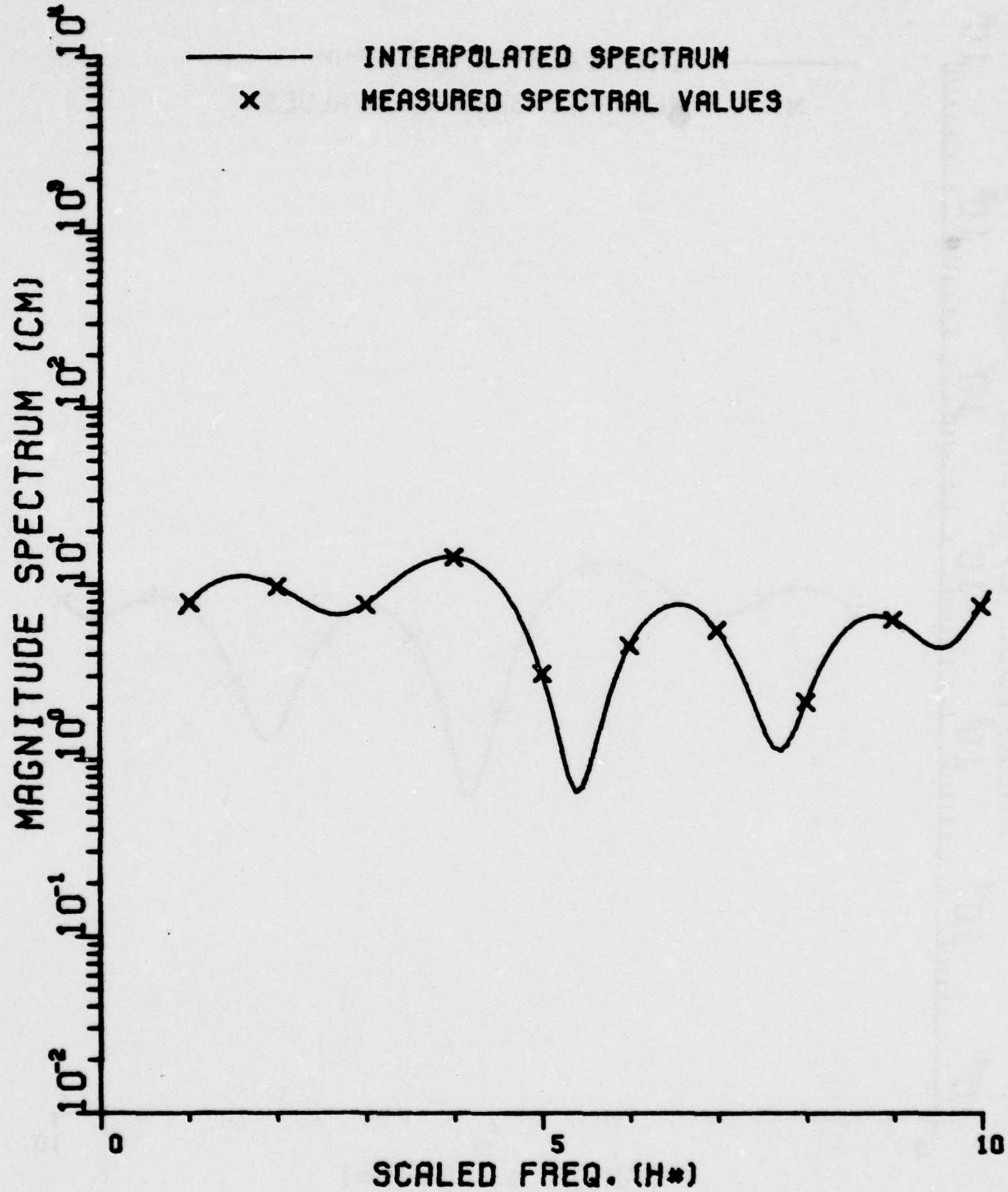

Figure 3j. 1/700 scale Missouri, 175^{0} from bow-on.

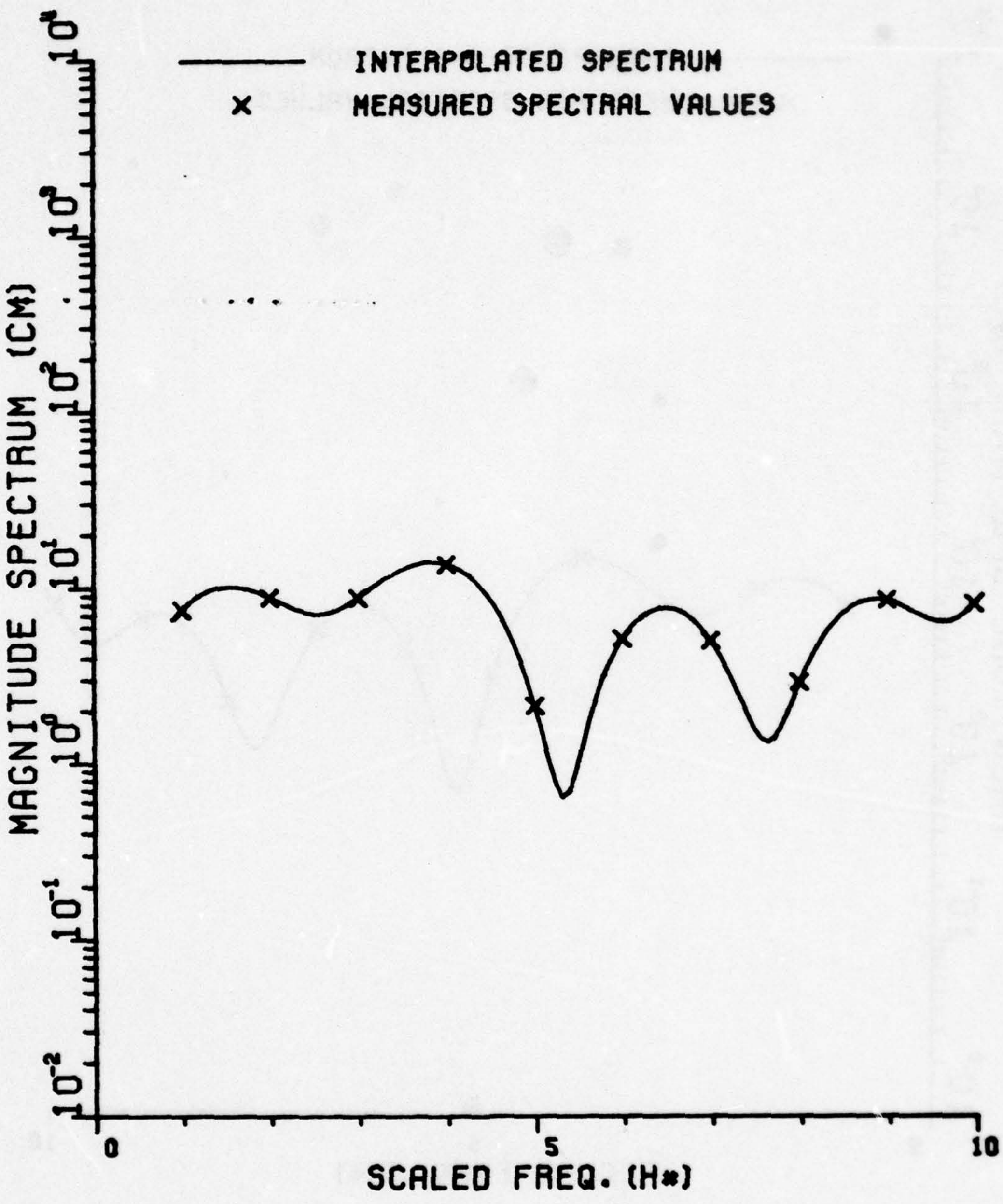

Figure 3k. 1/700 scale Missouri, 180^{o} from bow-on.

precise placement of the model during successive data taking runs to obtain data in different frequency bands and is therefore a very exacting measurement. Numerous examples of the matched-filter response were given in previous reports on this contract [1,2] and the reader will not be burdened here with further extensive plots. For the sake of illustration one example is given in Figure 4 for the data in Figure 2a. While the

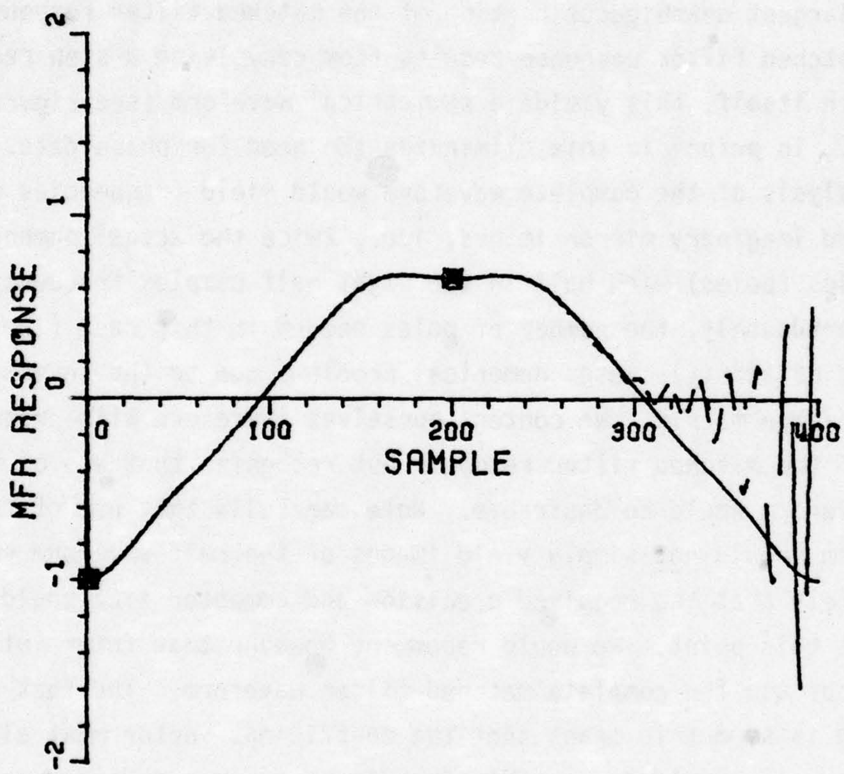

Figure 4. 1/500 scale Sverdlov, 0^{o} from bow, 15 poles, vertical scale 9.728/1.

matched filter response that satisfies our present purpose it is only one of many possible identification tools. Further research may point to other more meaningful waveforms. One such waveform is suggested in the recommendations section of this report.

Using the matched-filter responses, poles were extracted via Prony's method [1,2] using an interactive computer code developed at this facility. The poles were extracted from the region indicated as 1-200 on Figure 4 which corresponds to a full scale time span of 0.230μsec for the 1/500 scale models and 0.323μsec for the 1/700 scale models. This time span is the first half of the period of the fundamental interrogation frequency and is the largest unambiguous portion of the matched filter response. Since the matched filter response results from convolving a step response waveform with itself, this yields a symmetrical waveform (see Figure 4, solid line). In principle this eliminates the need for phase data. Ideally, analysis of the complete waveform would yield frequencies with both real and imaginary mirror images, i.e., twice the actual number of frequencies (poles) with half in the right half complex frequency plane. Unfortunately, the number of poles needed in this case (in the neighborhood of thirty) causes numerical problems due to the inversion of a rather large matrix. We content ourselves therefore with processing only half of the matched filter response but recognize that use of the complete waveform would be desirable. Note carefully that use of the full waveform should <u>not</u> simply yield images of the half-waveform results. It was not felt that the required precision and computer size could be justified at this point. We would recommend however that future utilization of our methods use the complete matched filter waveform. The fact that the waveform is symmetric means that the coefficient vector must also be symmetric. It should be possible therefore, using a modified analysis, to utilize the complete matched filter response waveform without doubling the size of the coefficient vector. It is intended to study the modifications necessary for this analysis.

Since both poles and residues are extracted with the present process [1,2] we are able to reconstruct the approximations to the original waveform. An example of a reconstructed matched filter response is given by the dashed line in Figure 4. Using the pole extraction program, several sets of poles were extracted from a given waveform by varying the unspecified parameters. Using each set of poles and the matched filter waveform a correlation coefficient curve was calculated as

$$\rho''(\Delta t) = 1 - \frac{\sum_n \left[F_{RM}(n\Delta t) - F_{RC}(n\Delta t)\right]^2}{\sum_n F_{RM}^2(n\Delta t) + \sum_n F_{RC}^2(n\Delta)} \qquad (2)$$

where F_{RM} is the matched filter response and F_{RC} is a response calculated using the poles, the matched filter response and Corrington's or Prony's difference equation [1,2]. The pole set used to specify the target in our library of poles is defined to be the one which maximizes the average of the correlation coefficient over all possible values of the sample interval Δt [2]. A summary of the resulting poles is given in Tables I and II. It should be noted that the poles in these tables have been scaled such that their imaginary parts are in mega-radians per second. Furthermore, the poles are given in terms of the full scale frequencies for each model. For a given harmonic number ($1 \leq N \leq 10$) and a given scale factor (S = 500 or 700) the radian frequencies are

$$\omega_N = \frac{2\pi N}{S} \times 1.085 \times 10^9 \qquad (3)$$

where 1.085 GHz is the fundamental interrogation frequency. Since the interrogation frequencies should only excite resonances within a limited region we would expect the extracted poles to lie within a region whose maximum is approximately given by Equation (3) with N equal to ten. Thus for

$$\omega_{MAX,500} \approx 136 \text{ Mrad/sec} \qquad (4)$$

$$\omega_{MAX,700} \approx 97 \text{ Mrad/sec.} \qquad (5)$$

Inspecting Tables I and II carefully it can be seen that almost all the poles having appreciable residue magnitudes satisfy these criteria. The poles having imaginary parts in excess of the limits are generally termed "curve fitting poles" and are typically associated with noisy data. It is hoped that data record combination techniques such as those to be discussed will help to remedy these problems as an automated

TABLE I
Poles of the 1/500 Sverdlov

NSTART : 1
NLAST : 200

	POLES				AND RESIDUES			
0^0	-1.7433E	0	-1.1873E	1	-4.9980E	0	1.5469E	0
	-1.7433E	0	1.1873E	1	-4.9980E	0	-1.5469E	0
	-5.5050E	1	3.7408E	-6	6.3057E	-1	8.0381E	-6
	-1.1162E	1	-8.6146E	1	-9.1175E	-2	-1.0841E	-1
	-1.1162E	1	8.6146E	1	-9.1176E	-2	1.0841E	-1
	4.0418E	0	-5.4904E	1	-1.0497E	-1	8.8294E	-3
	4.0418E	0	5.4904E	1	-1.0497E	-1	-8.8295E	-3
	-3.0152E	2	-6.0124E	2	4.2627E	-2	3.5509E	-2
	-1.0709E	2	6.0124E	2	-1.4744E	-2	1.2285E	-2
	-1.8146E	1	1.3469E	2	1.1890E	-3	-3.7032E	-3
	-1.8146E	1	-1.3469E	2	1.1892E	-3	3.7026E	-3
	8.9574E	0	-4.8893E	2	-8.8685E	-5	1.9554E	-6
	8.9574E	0	4.8893E	2	-8.8684E	-5	-1.9564E	-6
	3.4143E	1	3.3776E	2	2.3885E	-7	1.1378E	-6
	3.4143E	1	-3.3776E	2	2.3886E	-7	-1.1378E	-6
5^0	-1.9775E	0	1.4529E	1	-3.8774E	0	-1.4271E	-1
	-1.9775E	0	-1.4529E	1	-3.8774E	0	1.4271E	-1
	-9.2067E	0	5.7223E	1	-3.3798E	-1	2.2249E	-1
	-9.2067E	0	-5.7223E	1	-3.3798E	-1	-2.2249E	-1
	-2.9607E	0	8.3610E	1	-7.7412E	-2	4.8608E	-3
	-2.9607E	0	-8.3610E	1	-7.7412E	-2	-4.8608E	-3
	-1.3434E	0	-1.3080E	2	-1.7500E	-3	-1.9700E	-3
	-1.3434E	0	1.3080E	2	-1.7500E	-3	1.9700E	-3
	-2.6663E	1	-4.9231E	2	-8.2341E	-4	-1.6164E	-3
	-2.6663E	1	4.9231E	2	-8.2343E	-4	1.6164E	-3
	3.1626E	1	2.6559E	-7	4.8545E	-4	2.3107E	-10
	2.0822E	1	-4.0205E	2	-1.0427E	-5	-5.6903E	-6
	2.0822E	1	4.0205E	2	-1.0427E	-5	5.6903E	-6
	7.6517E	1	-5.6024E	2	-7.8450E	-11	-5.9299E	-11
10^0	-2.6263E	0	1.5873E	1	-4.0282E	0	4.6512E	-1
	-2.6263E	0	-1.5673E	1	-4.0282E	0	-4.6512E	-1
	-2.1725E	0	-5.5377E	1	-1.9807E	-1	-2.5051E	-2
	-2.1725E	0	5.5377E	1	-1.9807E	-1	2.5051E	-2
	-6.2356E	0	-8.6117E	1	-1.1180E	-1	-4.2959E	-2
	-6.2356E	0	8.6117E	1	-1.1180E	-1	4.2959E	-2
	2.1071E	1	1.0296E	-6	1.2213E	-2	1.8041E	-9
	-4.2704E	1	-3.4516E	2	-1.5904E	-3	-8.2025E	-3
	-4.2704E	1	3.4516E	2	-1.5903E	-3	8.2025E	-3
	-1.6459E	1	-4.9142E	2	-1.6724E	-3	-2.6601E	-3
	-1.6459E	1	4.9142E	2	-1.6724E	-3	2.6601E	-3
	1.2246E	1	-1.2511E	2	-3.0276E	-4	1.8955E	-4
	1.2246E	1	1.2511E	2	-3.0276E	-4	-1.8955E	-4

NSTART : 1
NLAST : 200

	POLES				AND	RESIDUES			
80^0	-5.7888E	0	-9.2768E	0		-3.3645E	1	2.5812E	1
	-5.7888E	0	9.2768E	0		-3.3645E	1	-2.5812E	1
	-2.9203E	1	1.2260E	-6		2.5696E	1	1.0063E	-5
	-5.2661E	0	6.0910E	1		-1.6879E	0	-4.1984E	-1
	-5.2661E	0	-6.0910E	1		-1.6879E	0	4.1984E	-1
	-2.3643E	1	-9.8611E	1		-6.1652E	-1	-9.3170E	-1
	-2.3643E	1	9.8811E	1		-6.1652E	-1	9.3169E	-1
	-2.2326E	0	-1.3689E	2		-1.8462E	-1	-8.9223E	-2
	-2.2326E	0	1.3689E	2		-1.8462E	-1	8.9223E	-2
	-5.3637E	1	5.4235E	2		3.1584E	-3	-1.7259E	-2
	-5.3637E	1	-5.4235E	2		3.1584E	-3	1.7259E	-2
	-1.2034E	1	3.4858E	2		6.0742E	-4	-3.7035E	-3
	-1.2034E	1	-3.4858E	2		6.0742E	-4	3.7035E	-3
	1.0150E	2	5.0529E	2		1.3464E	-12	7.4597E	-13
	1.0150E	2	-5.0529E	2		1.3464E	-12	-7.4594E	-13
85^0	-1.8112E	1	1.3727E	1		-4.0712E	1	4.6426E	1
	-1.8112E	1	-1.3727E	1		-4.0712E	1	-4.6426E	1
	3.0800E	0	-9.2638E	-6		1.6365E	1	2.6791E	-5
	-6.4898E	0	-1.0897E	2		-1.3060E	0	-2.9354E	-1
	-6.4898E	0	1.0897E	2		-1.3060E	0	2.9354E	-1
	-1.9629E	1	8.6483E	1		-5.2834E	-1	1.2173E	0
	-1.9629E	1	-8.6483E	1		-5.2834E	-1	-1.2173E	0
	-9.9645E	-1	-1.3684E	2		-1.6904E	-1	-6.1991E	-2
	-9.9645E	-1	1.3684E	2		-1.6904E	-1	6.1991E	-2
	-5.7404E	1	-4.2790E	2		-2.7772E	-3	-5.8439E	-3
	-5.7404E	1	4.2790E	2		-2.7777E	-3	5.8435E	-3
	3.4311E	1	1.7102E	-6		-8.8826E	-4	7.0193E	-9
	-1.5710E	0	-5.3522E	2		-2.0275E	-4	4.3487E	-6
	-1.5710E	0	5.3522E	2		-2.0270E	-4	-4.3414E	-6
90^0	-5.9731E	0	-3.7862E	0		-2.0605E	1	6.4135E	1
	-5.9730E	0	3.7862E	0		-2.0604E	1	-6.4135E	1
	-1.2848E	1	4.6084E	1		-3.9105E	0	1.0023E	1
	-1.2848E	1	-4.6084E	1		-3.9105E	0	-1.0023E	1
	-1.3255E	1	8.3013E	1		-3.2818E	0	-8.5123E	-1
	-1.3255E	1	-8.3013E	1		-3.2818E	0	8.5123E	-1
	-5.7993E	0	1.2638E	2		-1.0522E	0	5.9469E	-1
	-5.7993E	0	-1.2638E	2		-1.0522E	0	-5.9469E	-1
	3.3218E	0	-1.3930E	2		-7.6434E	-2	4.6697E	-3
	3.3218E	0	1.3930E	2		-7.6434E	-2	-4.6701E	-3
	-4.8797E	1	-5.1174E	2		-6.1637E	-4	-1.3004E	-3
	-4.8797E	1	5.1174E	2		-6.1318E	-4	1.2995E	-3
	-1.6215E	1	-3.8617E	2		8.6128E	-5	-4.8993E	-4
	-1.6215E	1	3.8617E	2		8.5435E	-5	4.9001E	-4
	7.5350E	0	6.0124E	2		-4.5275E	-5	3.7686E	-5

NSTART : 1
NLAST : 200

	POLES				AND RESIDUES			
95°	-3.4491E	0	-9.5276E	0	-2.5521E	1	1.9518E	1
	-3.4491E	0	9.5276E	0	-2.5521E	1	-1.9518E	1
	-2.1866E	1	-9.1815E	1	-6.7430E	0	-9.8284E	-1
	-2.1866E	1	9.1815E	1	-6.7430E	0	9.8284E	-1
	-1.2723E	1	4.3223E	1	-1.0728E	-2	2.9306E	0
	-1.2723E	1	-4.3223E	1	-1.0732E	-2	-2.9305E	0
	-1.1659E	1	1.2794E	2	-9.5079E	-1	1.6358E	0
	-1.1659E	1	-1.2794E	2	-9.5079E	-1	-1.6358E	0
	2.2131E	0	1.4506E	2	-6.8878E	-3	4.4060E	-2
	2.2131E	0	-1.4506E	2	-6.8877E	-3	-4.4060E	-2
	-1.6278E	2	6.0124E	2	1.5250E	-3	-1.2685E	-3
	-1.2492E	1	5.2632E	2	-2.1511E	-4	-4.0626E	-5
	-1.2492E	1	-5.2632E	2	-2.1513E	-4	4.0422E	-5
	2.2544E	1	-3.8242E	2	1.1691E	-5	-2.3244E	-6
	2.2544E	1	3.8242E	2	1.1691E	-5	2.3244E	-6
100°	-1.6285E	0	-1.2117E	1	-2.5189E	1	7.3245E	0
	-1.6285E	0	1.2117E	1	-2.5189E	1	-7.3245E	0
	-1.8996E	1	8.8776E	1	-5.1753E	0	1.6223E	0
	-1.8996E	1	-8.8776E	1	-5.1753E	0	-1.6223E	0
	-8.0782E	0	1.2810E	2	-6.0829E	-1	8.1071E	-1
	-8.0782E	0	-1.2810E	2	-6.0829E	-1	-8.1071E	-1
	2.0120E	0	-5.2943E	1	-1.3066E	-1	2.5432E	-1
	2.0120E	0	5.2943E	1	-1.3066E	-1	-2.5432E	-1
	-2.7443E	1	5.0596E	2	-7.2334E	-4	5.4281E	-3
	-2.7443E	1	-5.0596E	2	-7.2323E	-4	-5.4281E	-3
	-2.3957E	1	6.0124E	2	-3.8423E	-3	3.2011E	-3
	1.9856E	1	1.3705E	2	6.1210E	-4	-3.0951E	-4
	1.9856E	1	-1.3705E	2	6.1210E	-4	3.0950E	-4
	-1.8951E	0	3.9648E	2	8.3691E	-6	6.2323E	-4
	-1.8951E	0	-3.9648E	2	8.3720E	-6	-6.2320E	-4
170°	-1.2515E	0	1.2316E	1	-7.6630E	0	-1.5879E	0
	-3.1816E	1	-1.8696E	-6	1.6334E	0	-3.1529E	-6
	-1.1313E	1	-9.0697E	1	-5.7573E	-2	-5.4315E	-2
	-1.1313E	1	9.0697E	1	-5.7573E	-2	5.4315E	-2
	1.9356E	0	6.5431E	1	-6.1885E	-2	-4.6326E	-2
	1.9356E	0	-6.5431E	1	-6.1885E	-2	4.6326E	-2
	-3.8294E	0	-1.3460E	2	-1.2989E	-2	-4.4423E	-3
	-3.8294E	0	1.3460E	2	-1.2989E	-2	4.4424E	-3
	-5.3042E	1	-4.6379E	2	-9.5823E	-4	9.7105E	-3
	-5.3042E	1	4.6379E	2	-9.5769E	-4	-9.7105E	-3
	-2.0091E	1	-5.3082E	2	3.3451E	-3	6.5551E	-4
	-2.0091E	1	5.3082E	2	3.3452E	-3	-6.5533E	-4
	4.9104E	0	-3.5000E	2	8.6171E	-6	-9.6123E	-5
	4.9104E	0	3.5000E	2	8.6324E	-6	9.6120E	-5

NSTART : 1
NLAST : 200

POLES AND RESIDUES

	-1.0674E	1	8.5005E	0	-4.4725E	1	4.2352E	1
	-1.0674E	1	-8.5005E	0	-4.4725E	1	-4.2352E	1
	-2.8570E	0	1.5817E	-7	4.4129E	1	-2.6226E	-6
	-6.6321E	0	7.2742E	1	-1.1541E	0	5.8576E	-1
	-6.6321E	0	-7.2742E	1	-1.1541E	0	-5.8576E	-1
	-7.2475E	-1	-4.2308E	1	-1.0996E	0	-4.6534E	-1
80°	-7.2475E	-1	4.2308E	1	-1.0996E	0	4.6534E	-1
	4.5551E	-1	9.8143E	1	-7.4799E	-2	1.1020E	-2
	4.5551E	-1	-9.8143E	1	-7.4799E	-2	-1.1020E	-2
	-3.1658E	1	-3.3666E	2	4.5119E	-4	-5.0079E	-3
	-3.1658E	1	3.3666E	2	4.5113E	-4	5.0079E	-3
	-1.9881E	1	4.0017E	2	-2.8061E	-3	2.1211E	-3
	2.1571E	0	2.6197E	2	-1.2341E	-4	-2.9804E	-5
	2.1571E	0	-2.6197E	2	-1.2341E	-4	2.9803E	-5
	-4.3154E	0	7.5238E	0	-2.6323E	1	-2.0606E	1
	-4.3154E	0	-7.5238E	0	-2.6323E	1	2.0606E	1
	-3.1293E	1	-6.6007E	1	-1.8536E	0	-3.8349E	0
	-3.1293E	1	6.6007E	1	-1.8536E	0	3.8349E	0
	-1.8113E	0	-5.7190E	1	1.1937E	0	6.2463E	-3
	-1.8113E	0	5.7190E	1	1.1937E	0	-6.2467E	-3
	-9.7182E	0	9.2422E	1	-2.5108E	-2	7.7056E	-1
85°	-9.7182E	0	-9.2422E	1	-2.5109E	-2	-7.7056E	-1
	-1.8009E	2	-2.2579E	2	-6.2456E	-3	-6.3465E	-2
	-1.8009E	2	2.2579E	2	-6.2435E	-3	6.3464E	-2
	-4.3456E	1	-4.2946E	2	-2.6322E	-3	-2.1928E	-3
	1.2258E	1	2.9299E	2	-1.5039E	-4	-6.2130E	-5
	1.2258E	1	-2.9299E	2	-1.5039E	-4	6.2118E	-5
	2.8544E	1	8.1142E	-7	1.6257E	-4	1.1703E	-9
	3.5014E	1	4.2946E	2	-1.9464E	-7	1.6215E	-7
	-9.7415E	0	-1.5662E	1	-3.3654E	1	-1.7679E	1
	-9.7415E	0	1.5662E	1	-3.3654E	1	1.7679E	1
	6.5817E	-1	8.3122E	-7	9.6338E	0	-1.3720E	-6
	-4.1851E	0	-7.6496E	1	-2.3836E	0	-8.4496E	-1
	-4.1851E	0	7.6496E	1	-2.3836E	0	8.4496E	-1
	4.0559E	0	5.2361E	1	2.7969E	-1	1.3020E	-2
90°	4.0559E	0	-5.2361E	1	2.7969E	-1	-1.3020E	-2
	6.7003E	-1	-9.7733E	1	-1.7707E	-1	-3.5909E	-3
	6.7003E	-1	9.7733E	1	-1.7707E	-1	3.5908E	-3
	-2.6340E	2	-4.0017E	2	-1.0720E	-2	-8.0396E	-3
	-2.4200E	1	2.9726E	2	1.1630E	-3	-1.2728E	-4
	-2.4200E	1	-2.9726E	2	1.1629E	-7	1.2671E	-4
	1.0035E	0	3.5978E	2	1.5199E	-4	1.0895E	-5
	1.0035E	0	-3.5978E	2	1.5199E	-4	-1.0883E	-5

NSTART : 1
NLAST : 200

	POLES				AND RESIDUES			
	-6.3383E	0	-1.5964E	1	-4.2690E	1	-6.8857E	1
	-1.1488E	2	-4.0017E	2	5.5045E	1	3.8477E	1
	-5.1676E	0	7.3229E	-6	5.3531E	1	3.5008E	0
	-7.9435E	0	-6.4090E	1	-4.3095E	1	-1.1953E	1
	-7.9435E	0	6.4090E	1	-1.6817E	1	-4.7422E	0
	-6.3383E	0	1.5964E	1	6.9515E	-1	1.2328E	1
95^{0}	-2.9618E	0	7.8652E	1	8.0535E	0	3.0926E	0
	-2.9618E	0	-7.8652E	1	3.3184E	0	7.6860E	0
	-2.1974E	0	9.6867E	1	1.4469E	0	6.6152E	0
	-2.1974E	0	-9.6867E	1	9.3487E	-1	-2.0603E	0
	2.1357E	1	3.3963E	2	-3.6142E	-3	-3.0992E	-4
	2.1357E	1	-3.3963E	2	-1.7907E	-3	2.9103E	-3
	4.6028E	1	-2.6672E	-7	-1.2513E	-5	2.2686E	-6
	6.7324E	2	1.9007E	-11	-1.4899E	-36	-8.1405E	-37
	-4.1353E	0	1.5917E	1	-1.8110E	1	2.9539E	0
	-4.1353E	0	-1.5917E	1	-1.8110E	1	-2.9539E	0
	-1.7329E	1	5.0821E	1	-2.3718E	0	2.6818E	-1
	-1.7329E	1	-5.0821E	1	-2.3718E	0	-2.6819E	-1
	-7.7451E	0	-8.1619E	1	-4.0104E	-1	-7.8991E	-1
	-7.7451E	0	8.1619E	1	-4.0104E	-1	7.8991E	-1
	1.2377E	0	-9.5927E	1	-1.5190E	-1	7.1861E	-2
100^{0}	1.2377E	0	9.5927E	1	-1.5190E	-1	-7.1861E	-2
	1.8547E	1	2.6398E	-7	1.7161E	-2	3.0099E	-9
	-7.1817E	1	2.2361E	2	6.5554E	-3	-8.3278E	-3
	-7.1817E	1	-2.2361E	2	6.5552E	-3	8.3278E	-3
	1.9923E	1	3.2861E	2	-3.1580E	-6	1.0299E	-5
	1.9923E	1	-3.2861E	2	-3.1585E	-6	-1.0299E	-5
	2.4559E	1	3.9387E	2	7.6317E	-7	-3.1661E	-6
	2.4559E	1	-3.9387E	2	7.6330E	-7	3.1660E	-6
	-3.3234E	0	-7.4070E	0	-1.6893E	0	1.1979E	0
	-3.3234E	0	7.4070E	0	-1.6893E	0	-1.1979E	0
	-3.8857E	1	4.0334E	1	9.9420E	-2	1.8192E	-1
	-3.8857E	1	-4.0334E	1	9.9420E	-2	-1.8192E	-1
	1.9401E	0	-4.1458E	1	-8.8744E	-2	-4.9201E	-2
	1.9401E	0	4.1458E	1	-8.8744E	-2	4.9201E	-2
170^{0}	-3.1429E	0	9.4828E	1	-2.2040E	-2	1.0508E	-2
	-3.1429E	0	-9.4828E	1	-2.2040E	-2	-1.0508E	-2
	-3.3691E	1	-3.4298E	2	1.6841E	-4	2.2136E	-4
	-3.3691E	1	3.4298E	2	1.6841E	-4	-2.2135E	-4
	1.3985E	1	8.6183E	1	-1.4414E	-4	-7.5462E	-5
	1.3985E	1	-8.6183E	1	-1.4414E	-4	7.5463E	-5
	-1.4282E	1	-2.6009E	2	2.5507E	-5	1.1713E	-4
	-1.4282E	1	2.6009E	2	2.5508E	-5	-1.1713E	-4
	-1.4051E	1	4.2946E	2	7.3463E	-5	-6.1204E	-5

NSTART : 1
NLAST : 200

	POLES			AND	RESIDUES			
	-2.6593E	0	-9.1688E	0	-1.4994E	0	5.9373E	-1
	-2.6593E	0	9.1688E	0	-1.4994E	0	-5.9373E	-1
	-1.4517E	1	4.2542E	1	-2.4882E	-1	2.4551E	-1
	-1.4517E	1	-4.2542E	1	-2.4882E	-1	-2.4551E	-1
	3.6426E	0	-4.5899E	1	2.3324E	-3	-4.8386E	-2
	3.6426E	0	4.5899E	1	2.3324E	-3	4.8386E	-2
175°	-2.3764E	0	9.6229E	1	-1.4178E	-2	4.9844E	-3
	-2.3764E	0	-9.6229E	1	-1.4178E	-2	-4.9844E	-3
	-2.9788E	1	3.7069E	2	9.4630E	-5	-6.4736E	-5
	1.3381E	1	-3.1077E	2	5.2744E	-6	-1.5043E	-6
	1.3381E	1	3.1077E	2	5.2745E	-6	1.5039E	-6
	4.2496E	1	-8.0795E	1	6.7451E	-9	-8.3941E	-9
	4.2496E	1	8.0795E	1	6.7451E	-9	8.3937E	-9
	-5.7251E	0	-1.5093E	1	-1.3578E	0	-5.8504E	-1
	-5.7251E	0	1.5093E	1	-1.3578E	0	5.8504E	-1
	-1.4016E	0	3.5966E	1	-2.7166E	-1	-2.9992E	-2
	-1.4016E	0	-3.5966E	1	-2.7166E	-1	2.9993E	-2
	-3.7803E	0	-9.4393E	1	-2.5485E	-2	-1.1331E	-2
	-3.7803E	0	9.4393E	1	-2.5485E	-2	1.1331E	-2
180°	1.2244E	1	-8.2569E	-7	2.2697E	-2	1.6542E	-9
	-4.2225E	1	3.2634E	2	-3.4887E	-4	5.1174E	-3
	-4.2225E	1	-3.2634E	2	-3.4920E	-4	-5.1173E	-3
	-1.3590E	1	-4.0017E	2	-1.2928E	-3	-9.7713E	-4
	1.9863E	1	7.3663E	1	2.6889E	-5	4.2099E	-5
	1.9863E	1	-7.3663E	1	2.6889E	-5	-4.2099E	-5
	2.1962E	1	1.4753E	2	-6.5954E	-7	8.8202E	-7
	2.1962E	1	-1.4753E	2	-6.5958E	-7	-8.8189E	-7

technique and also reduce the number of entries in the pole library. It is stressed that all of the parameters extracted by the program are shown in the Tables. No attempt has been made to enhance the results by removing obviously erroneous poles nor do we choose to plot only those results which obviously support our conjectures. Admittedly, averaged results for the poles will be enhanced by a judicious choice of those poles to be included in the averaging but Tables I and II are shown unaltered to permit the reader to draw his own conclusions. We maintain that within the known limitations of the Prony method for noisy data the extracted poles as obtained by our approach do support the quasi-aspect invariance postulate.

The next step in the data analysis was to treat the poles in Tables I and II as a library of entries. Each harmonic data set was then treated as an unknown target data set and compared to all of the pole library entries, via the prediction-correlation procedure. The results of this test are given in Table III. For the harmonic data sets the prefixes "MIS" and "SVE" indicate the 1/700 scale Missouri and the 1/500 scale Sverdlov, respectively. The three digit suffix indicates the aspect of the data set in degrees from bow-on incidence. For the pole sets the prefixes "PMI" and "PSV" stand for the best pole sets of the Missouri and Sverdlov, respectively for the indicated aspect. The arrows indicate which pole set gave the best agreement for the criterion of maximizing the average value of the correlation coefficient, ρ'', over all possible sample values, Δt. Correct identifications are those for which a data set was matched with poles extracted from the given data set. A close identification is one for which the match wasn't with the poles from a given data set but with a set of poles from a data set within the aspect group of the data set in question. An incorrect identification is one in which a data set was not matched within the aspect group to which it belonged. Thus even though the aspect invariance postulate doesn't appear to hold exactly it should be possible to combine data sets within one of these broad aspect groups and significantly decrease the number of pole library entries. This prospect is enhanced by the absence of mis-identifications and the similarity of some of the pole sets within the aspect groups.

TABLE III

	Harmonic Data Set		Pole Set	
BOW	MIS000	→	PMI000	BOW
	005	→	005	
	010	→	010	
ABEAM	080	→	080	ABEAM
	085	→	085	
	090	→	090	
	095	→	095	
	100	→	100	
STERN	170	→	170	STERN
	175	→	170	
	180	→	170	
			175	
			180	
BOW	SVE000	→	PSV000	BOW
	005	→	005	
	010	→	PSV000	
			010	
ABEAM	080	→	080	ABEAM
	085	→	085	
	090	→	090	
	095	→	095	
	100	→	100	
STERN	170	→	170	STERN
	175	→	175	
	180	→	180	

# Correct	= 19	;	86.4%
# Close	= 3	;	13.6%
# Wrong	= 0	;	0 %

III. DATA RECORD COMBINATIONS

For a given span of real interrogating frequencies where the electrical size of the target is not too large, the target can be characterized by a finite set of complex natural resonances which are excitation invariant. Not all of the resonances however are strongly excited at any one aspect and it may not be possible to excite certain of the resonances at that aspect. This is particularly true for geometrically complicated structures such as naval vessels when the resonances of interest are physically related to certain complex substructures of the vessel.

The details of Prony's method, which extracts a set of complex natural resonances and residues from a given signal record, have been given [1,2]. With this approach a signal is modeled as a finite sum of exponentials*

$$f(t) \approx \sum_{n=1}^{N} A_n(\theta,\phi,\hat{p})\, e^{\gamma_n(t-t_o)}\, \mu(t-t_o) \tag{6}$$

and then the complex natural resonances

$$\gamma_n = \sigma_n \pm j\omega_n \tag{7}$$

and the aspect and polarization-dependent residues

$$A_n(\theta,\phi,\hat{p}) = A_{nr}(\theta,\phi,\hat{p}) \pm j\, A_{nq}(\theta,\phi,\hat{p}) \tag{8}$$

are extracted via a predictor-type difference equation (Prony's equation) [1,2]. There are difficulties with the method in that right half-plane poles (σ_n>0) and anomalous pattern-fitting poles can result. One also finds that the "poles" extracted from signals corresponding to different aspects of the same target are not precisely invariant. Usually the obvious "pattern fitting" poles are discarded and then an averaging of the remaining poles is used

*The delay t_o in Equation (6) is usually ignored mathematically but used physically.

$$\sigma_a \pm j\omega_a = \frac{1}{I}\sum_{i=1}^{I} \sigma_i \pm j\omega_i \tag{9}$$

for each obviously different pole location. The summand in Equation (9) refers to various aspects. This approach works reasonably well (identification [3,4]) but experience is helpful in deciding which pole locations should be averaged. There are other approaches which might be attempted. Suppose we have data at I aspects (i=1,2,...,I) then the waveforms could be combined as

$$f_a(t) = \frac{1}{I}\sum_{i=1}^{I} d_i f_i(t-T_i) \quad . \tag{10}$$

Some preshifting of the waveforms (T_i) is necessary because the usable portion of each signal record is generally dependent on aspect. A pre-weighting (d_i) may also be necessary if the amplitudes of the signals are widely different. Prony's method could then be used to extract one set of complex natural resonances from the averaged waveform. Note that averaging could reduce noise and/or clutter problems. Assuming the form of Equation (6) for each waveform

$$f_a(t) = \frac{1}{I}\sum_{i=1}^{I} d_i \sum_{n=1}^{N} A_n^i(\theta,\phi,\hat{p}) e^{\gamma_n(t-T_i)} \mu(t-T_i) \quad . \tag{11}$$

Ignoring the time-shifting of each waveform (mathematically)

$$f_a(t) = \frac{1}{I}\sum_{n=1}^{N} e^{\gamma_n t} \sum_{i=1}^{I} d_i A_n^i(\theta,\phi,\hat{p}), \tag{12}$$

i.e., obtaining an averaged waveform amounts to obtaining a weighted averaged residue value for each pole before processing by Prony's method. We have not tested this averaged waveform approach as yet.

If Prony's method is applied individually to each aspect as was done here then one obtains

$$\gamma_n^i = -\sigma_n^i \pm j\omega_n^i \qquad \begin{matrix} n=1,2,...N_i \\ i=1,2,...,I \end{matrix} \quad . \tag{13}$$

That is, a pole set is obtained for each aspect and the number of poles in the set can also vary with aspect depending upon the criterion of selection. Note that one also obtains the corresponding residues

$$A_n^i(\theta,\phi,\hat{\rho}) = A_{nr}^i(\theta,\phi,\hat{\rho}) \pm j\, A_{nI}^i(\theta,\phi,\hat{\rho}) \quad . \tag{14}$$

$$n=1,2,\ldots N^i$$
$$i=1,2,\ldots I$$

Some, but not all, of the poles in Equation (13) will show the "clustering" referred to earlier. A pole set is then obtained from the poles in Equation (13) using some combination of machine and operator processing. One reason for using this approach for the case of naval vessels is that very good success has previously been obtained with "clustered" poles for underground targets. As is seen elsewhere in this report, poles from the naval vessels do indeed show "clustering", but to date the identification results are, while not disappointing, clearly not optimum. It is not felt that our processing is complete to the extent that a clustered pole approach should be discarded at this point. We are, however, beginning to look at other methods for obtaining identification parameters, one of which is the averaged waveform or averaged residue concept discussed earlier.

The basic problem of processing numerous data records from the same object is being studied on a companion project [5]. The main thrust of these studies to date is that the most basic question to be answered is whether samples of a data record

$$f^i[m\delta t+(N-n)\Delta t] = f^i_{m\delta+(N-n)\Delta}$$
$$i=1,2,\ldots I \tag{15}$$

can approximately satisfy a homogeneous, linear difference equation

$$\sum_{n=0}^{N} f^i_{m\delta+(N-n)\Delta} a_n = \epsilon_m \;,$$
$$m = 0,1,2,\ldots M$$
$$i = 1,2,\ldots I \tag{16}$$

where ϵ_m is the error. There are N+2 different methods for solving for the coefficients, a_n, [5] each of which is a least squared error solution ($M>2N+1$) and one of which is the well-known Prony method. The Prony method incidently does not lead to the minimum totaled squared error but this of course is not the only basis for selection of a method. Equation (16) is slightly more general than the equation given in [5] in that the increment on m is not necessarily the same as on n. For our present purpose, the interest is in a suggested eigenanalysis method for combining records from several aspects by first finding that difference equation which best "fits" all of the data. It has already been demonstrated that this can be done [6,7] using chirp-type short pulse response waveforms from aircraft targets. It is intended to test the naval vessel data using this approach.

From a pole or complex natural resonance viewpoint the identification problem is complicated by the fact that we know from present results that for a given vessel at least three distinct pole subsets can be defined corresponding to aspects in the vicinity of bow-on, stern-on and abeam. It is not yet clear if these pole subsets should be treated as three separate subvessels, all of which identify the same vessel, or if the subsets should be combined to characterize the vessel and the processing permitted to reject the unused or unexcited poles. To date only the subvessel approach has been tested and then only incompletely. Given that a set of complex natural resonances can be used to characterize a given vessel (we absorb the as yet unanswered question of several subsets vs. one larger set) it follows that there are many possible ways to identify the target. The prediction-correlation identification process developed here has worked better than any other method we have tried. It has the additional very real advantage that it is not necessary to extract poles from some unknown target record. This does not mean of course that a better method of identification processing might not be found in the future.

IV. THE ENCAPSULATED SOURCE AND RECEIVER

A major problem with the identification techniques presented is obtaining characteristic waveforms for the targets in question. Once this is accomplished, then using Prony's method or some similar method the poles may be extracted and identification can be accomplished. For this project the signaling waveforms have been produced via Fourier synthesis of discrete frequency measurements of scaled model targets. As we attempt to go to higher frequencies practical limits for an experimental system are quickly reached. As explained earlier we have modeled the ocean environment by a highly conducting ground plane. Even at the frequencies being used now this model is in question and the problem will become more serious at higher frequencies. Also, as larger models are used the problem of setting up a measurement system which can accurately measure the scattered field from the targets becomes increasingly difficult.

With larger targets the problems of near field effects become more serious. The required distances to alleviate this problem would make an experimental system impractical. This problem would become even more formidable if it becomes necessary to look at the targets from many different aspects. It has been suggested [9,10] that a measurement system utilizing an encapsulated source and receiver could be used to obtain characteristic waveforms of the targets. Obviously encapsulating the source and receiver does not correct the sea model (ground plane) at high frequencies. The point however is that encapsulated source-receiver techniques, when fully developed, could be applied to full scale targets in situ. In Figure 5 is shown a simplified diagram of a system using this concept. This system is similar to those developed for use in the area of underground radar [12]. A short pulse source is used to excite the target and a sampling scope is used to record the resulting forced response and transient. Typically the forced response is many times greater in magnitude than the transient portion. Thus if sensitivity in the transient region is not to be sacrificed then some method must be found to protect the sampling

ENCAPSULATED SOURCE AND RECEIVER

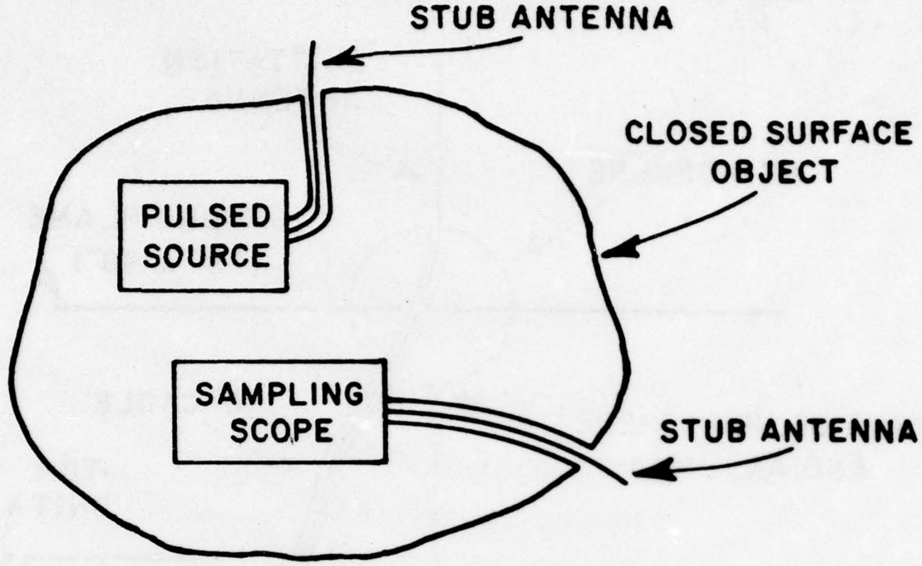

Figure 5.

head. In the underground radar system this is done by using crossed dipoles as the excitation and receive antennas. The receiver dipole, being significantly decoupled from the excitation dipole, picks up a transient response which is large enough to be accurately read but rejects the major portion of the target's forced response. In the case of the encapsulated source and receiver it would be possible to use two antennas although one antenna would be more convenient for a full scale system. However the crossed dipole system or an analogous type of isolating system would be difficult to implement. This then complicates the measurement system which is contrary to our purpose.

In Figure 6 is shown a simplified system we have tried which utilizes a modified version of the encapsulated source and receiver concept. This system uses a time-domain-reflectometry (TDR) unit which is connected via a six foot section of coaxial cable to a stub antenna on a target. The TDR unit sends out a series of short pulses (in this case a tektronix TDR unit has been used with a pulse length of approximately 120 picoseconds).

TDR MEASUREMENT SYSTEM

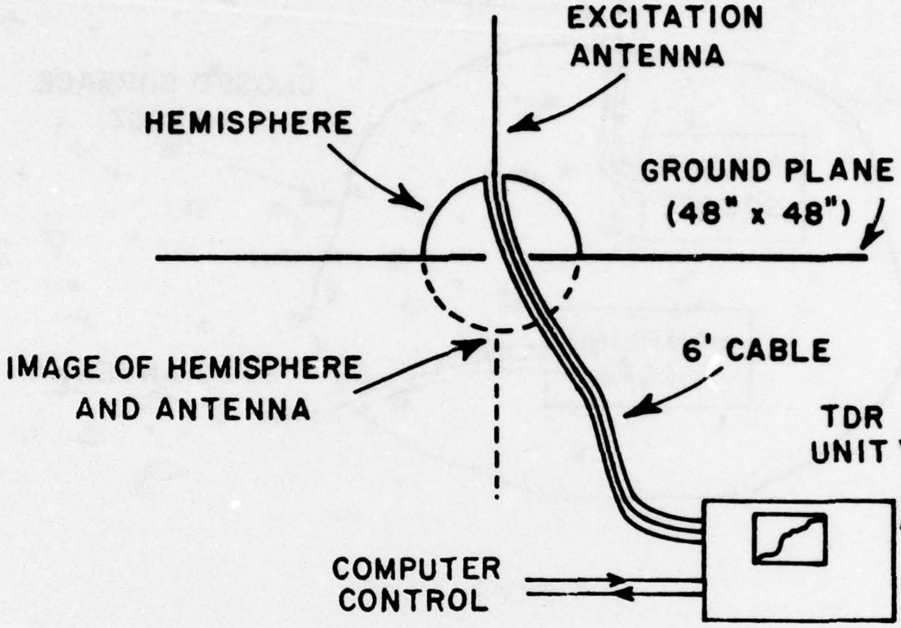

Figure 6.

A sampling scope is used to sample the reflected energy from down the line. The output is a continuous waveform showing reflection coefficient as a function of time (or range if the velocity of propagation in the medium is known). In the case of the hemisphere on the finite ground plane shown in Figure 6 we are interested in the region of the response due to the stub-hemisphere connection and beyond. In this broad region we can expect several subregions of interest. First there will be a sharply increasing region due to the transition from the cable center conductor surrounded by a dielectric to the stub antenna which is in free space (see Figure 7). Next there will be a region of special interest. This should be a series of oscillations in impedance due to reflections from the ground plane. Note that the period of the oscillation is dependent on the size of the sphere and is therefore characteristic of it. We will also expect a return from the edge of the ground plane which should be far enough away to be isolated from the hemisphere oscillations.

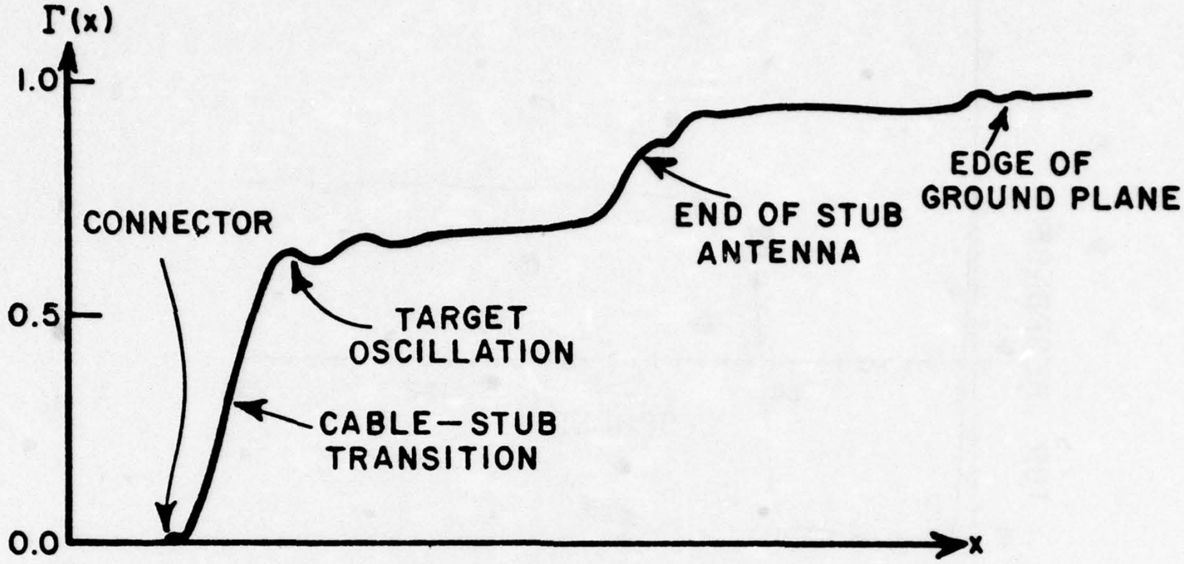

Figure 7. Example of TDR response.

There will also be oscillations due to returns from the end of the stub antenna. If the antenna is *too short then* these oscillations could interfere with those due to the hemisphere. Lastly there will be a constant section which is indicative of complete transition to free space.

In Figure 8a,b,c are shown the TDR responses of a 7.05 inch diameter hemisphere on a 48 x 48 inch square metal plate. The stub lengths are 0.78 inches, 3.00 inches and 29.25 inches respectively. In Figures 8a and 8b it is easily seen that the oscillations due to the antennas tend to cover up those of the hemisphere. In Figure 8c the response of the hemisphere is easily distinguishable from the returns due to the edge of the ground plane. For this reason all processing has been done on the response in Figure 8c. This method of isolating the target response from the antenna response is easily done for the case of the small hemisphere but whould be impractical for large targets. It is felt that it might be possible to subtract this out using a difference equation approach and careful modeling of the cable-antenna transition. Further work is anticipated in this area.

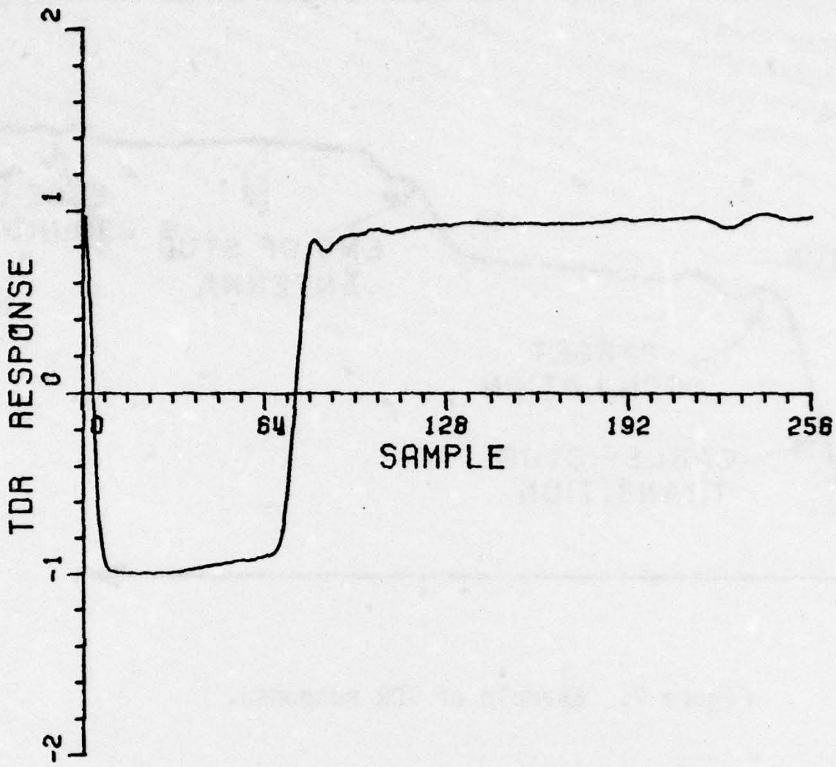

Figure 8a. 7.05" hemisphere with 0.875" stub.

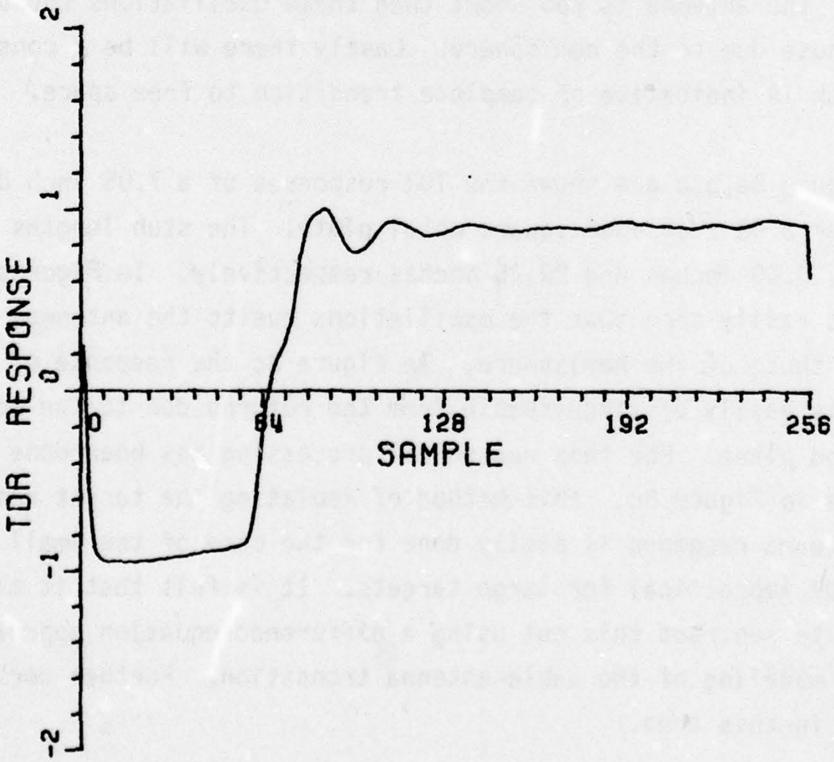

Figure 8b. 7.05" hemisphere with 3" stub.

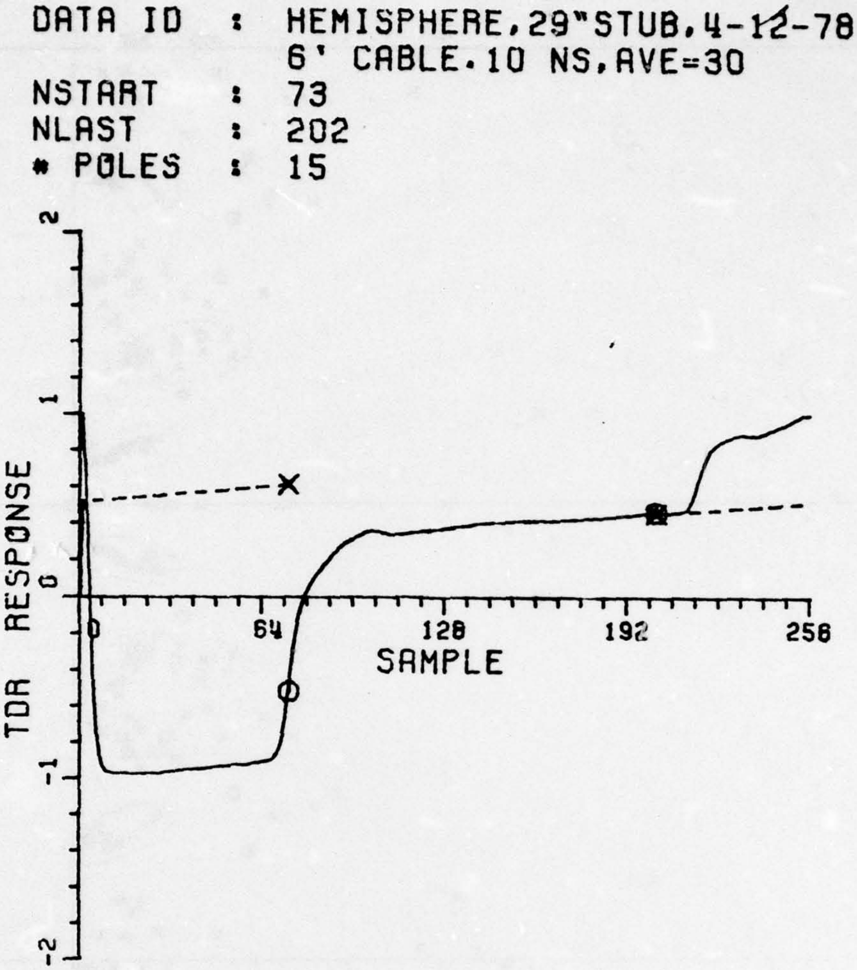

Figure 8c.

Included with Figure 8c is a waveform constructed from poles extracted via Prony's method. In this case the fit to the waveform was very good and over the interval of application the measured and reconstructed waveforms are virtually identical (the reconstructed waveform is given by the dashed line). By varying the number of poles requested and the interval ([2], Section V) many pole pairs were extracted. The results of this operation are shown as a plot, Figure 9, of the pole positions in the complex plane. It should be noted that there is a definite clustering effect of the poles. Also there are many spurious points that can be associated with curve fitting poles which generally have very small residues associated with them. Also plotted in Figure 9 are the pole positions for the 7.05 inch sphere as obtained by Stratton

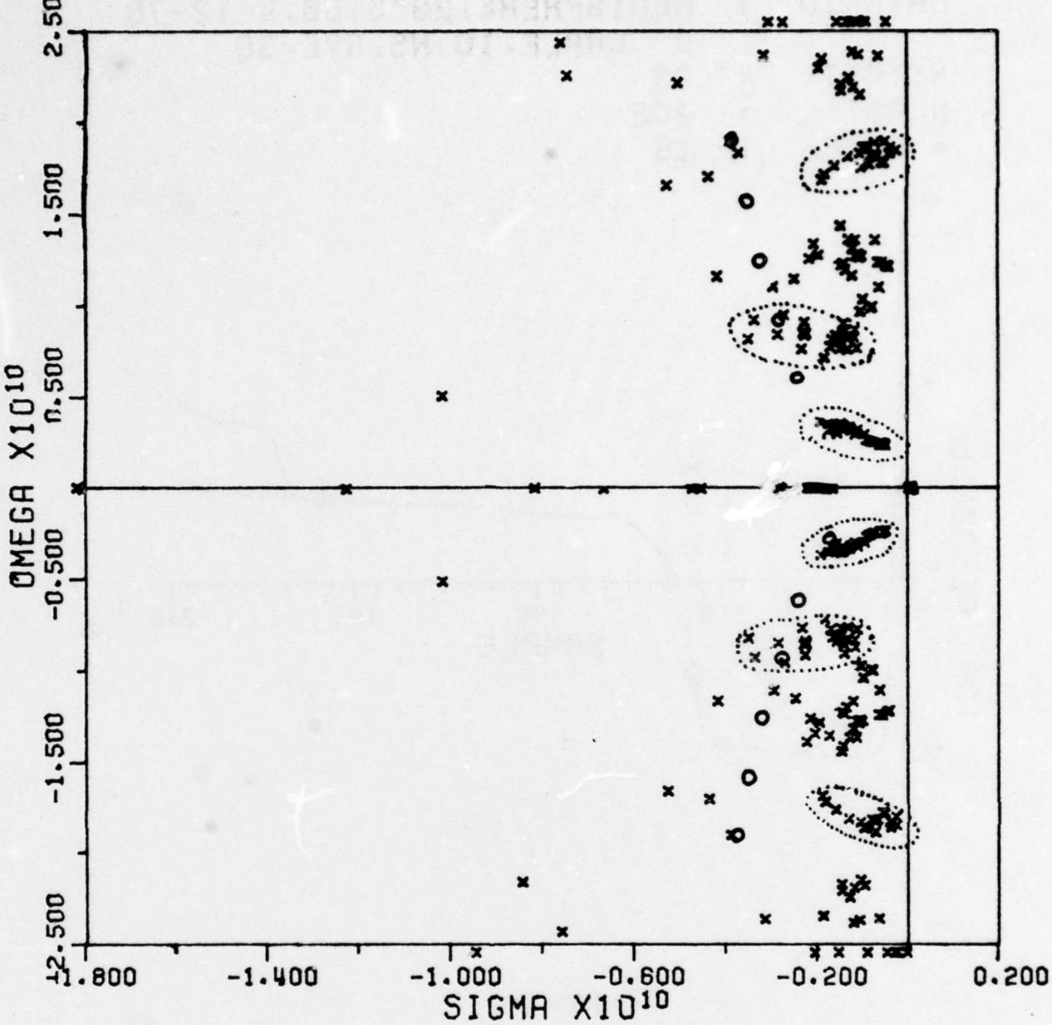

Figure 9. Poles of a 7.05" hemisphere via Prony's method.

[11]. Due to the stub excitation we would expect to excite the transverse magnetic (TM) resonances of the spherical body. The effect of the ground plane will be to short out the even mode resonances. Thus we will expect to see the odd, TM modes. From Figure 9 it can be seen that there is a definite clustering of the poles about the TM_1 and TM_3 resonances. There is quite a spread in the real parts of the poles but fairly good agreement for the imaginary parts. For the TM_5 pole there is *no* cluster of poles near, however, there is a cluster at a slightly greater frequency with a real part approximately 40% of that of the true pole. This spread

of the real parts has been seen before when Prony's method has been used on noisy data. It is felt that these results are very promising due to the nature of the sphere which is almost a worst-case target. This is due to the high damping of the poles which results in very few oscillations compared to targets such as thin wires which show appreciable ringing for several cycles. For this reason it is planned to obtain measurements on other targets such as the prolate spheroid. This will also be cut in half and measured on the ground plane. Due to its long slender shape hopefully this target will ring more and be better suited to pole extraction techniques like Prony's method.

V. CONCLUSIONS AND RECOMMENDATIONS

The following conclusions can be drawn from the factual data sections of this report.

1. The feasibility of naval vessel identification via complex natural resonances associated with substructure features of the vessel has been demonstrated.

2. Identification capability has been extended to arbitrary aspects in the vicinity of bow-on, stern-on and abeam, i.e., the quasi-invariant postulates regarding previous results have been proven.

3. By implication, substructure complex natural resonances and prediction-correlation processing can be extended to arbitrary aspect angles but the number of resonance aspect positions for a given vessel, while small, is unknown.

4. Interactive programs based on Prony's method have been developed for extracting poles and residues from noisy transient response signals. The programs automate the selection of sample interval and pole number. These programs, while adequate for our present task, still display many of the known problems associated with Prony's method.

5. Other methods for extracting a set of poles and residues from several transient records corresponding to different target aspects have been suggested. Certain of these are being pursued on companion (JSEP) contracts.

6. Ten frequency harmonic scattering data on two naval vessel classes (cruiser and battleship) have been obtained for a variety of aspects spanning the bow-on, stern-on and abeam positions. These data served as test inputs for the extended identification procedures.

7. For two naval vessel classes and aspects in the vicinity of bow-on, stern-on or abeam probabilities of correct identification of 86 percent and probabilities of incorrect identification of 14 percent have now been obtained.*

8. The feasibility of using encapsulated source and receiver methods to obtain natural resonance rich transient signals has been demonstrated. These methods, when refined, could be used to obtain the complex natural resonances of large geometrically complicated structures in situ. Test results for conducting hemispherical geometries on a ground plane were extremely promising, i.e., the measured resonances were in good agreement with the known resonances.

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*These are conservative estimates of identification probabilities.

A fair summary of our present progress with regard to the radar identification of naval vessels can be stated in terms of what appears to be possible now with sophisticated full scale radar systems. Given a radar system capable of harmonically sampling the radar cross section of a naval vessel in situ over a frequency decade with the highest frequency less than 25 MHz, correct identification of the vessel with probabilities in the range 70 to 80 percent are postulated. While these correct identification probabilities are low, they are tempered by the fact that the probabilities of incorrect identification are remarkably low. In principle, these results are independent of the aspect and elevation angles of the radar and the target range. It is assumed that a vertically polarized radar is used. The frequency range of the system is such that the sea state, minor structural alterations of the vessel and the motion of the vessel are <u>not</u> factors which will contaminate or distort the identification process. A major consideration <u>is</u> obtaining the needed sampling of transient response waveforms of the vessel from which the identification parameters (substructure complex natural resonances) can be extracted. At the moment identification parameters on only two vessels (see Section V) are available and these are incomplete. Note carefully that transient data for extraction of the identification parameters need not be at any particular range, aspect or elevation, but must span discretely all possible major aspects. At the very least this would include the bow-on, abeam and stern-on regions plus angles 45° and 135° from bow-on. These conjectures are based on bistatic (10°) measurements but no significant alterations for true monostatic systems are anticipated.

Perhaps the most direct and immediate need for this, as well as other, radar identification programs is multiple frequency scattering data over appropriate spectral regions (very roughly hull lengths of 1.5 to 10 or 15 wavelengths). Some care has been taken to ensure that our scattering models are sound both geometrically and electromagnetically [1] and that the required frequencies for identification are at least feasible if not optimum from a practicality viewpoint. Unfortunately it is precisely this spectral range which dictates experimental data

as neither computer models nor asymptotic theories can be used in their present forms. Multiple frequency measurements of this type are tedious and time consuming. Additional details (frequencies) are also needed if the substructure features associated with a particular identification parameter are to be isolated. In essence, simple models and measurements may be adequate for feasibility studies but we are beyond that stage. It is desired to test our identification procedures over as broad a data base as possible (spanning at least several vessel classes for a variety of aspects, elevations and ranges) while at the same time refining our processing procedures. The recommendations listed below are directed toward these goals.

1. A continual testing of the available data base (two vessels) using different criteria to select the size and content of the identification parameter library. These procedures can and will be expanded to include new data as they become available.

2. New and unique discrete-swept scattering measurements of the naval vessels in situ now available. These are essentially swept frequency measurements but the frequency is stabilized and the background corrected at many discrete frequencies across the frequency span. For example, in the range 2.2 to 4.0 GHz (model frequencies) some 201 spot measurements are made. These measurement procedures have been automated and tested for free space targets and are presently being adjusted to the naval vessel range.

3. From the measured data in 2) above, synthetic pulse response waveforms can be synthesized. We propose to obtain resolutions such that the significant scatterers of the vessel can be isolated and the dominant substructure controlling resonances identified. The pulse response waveform envelopes will also permit certain nonphysical but possibly useful identification tests to be made. Details of the discrete-swept reflectivity facility are given in References [6,7], as are examples of envelope processing.

4. Analytical models for calculating the radar return from in situ vessel models are beginning to emerge [8]. While the ship models are still relatively simple and the ship scattering theory confined to first order diffraction, a nonsmooth sea surface and ship-sea iteraction are included. Thus the basic model would appear to be a correct basis for more sophisticated models. We would propose a beginning look at these models, perhaps by comparing our existing measurements with some simple computations. A carefully developed model which realistically (interactions) includes a model of a nonsmooth sea is a desirable and economically-wise alternative to very expensive and time-consuming measurements which cannot evaluate changing sea states. In addition, such models when developed could provide a significant data base. This item is viewed as a long term multi-year objective.

5. Certain moderate scale encapsulated source and receiver experiments should be made. Large models (dimensions of a meter roughly) of simple models such as cubes or parallelpipeds can be constructed with reasonable cost. The use of such models would permit bistatic arrangements of source and receiver probes thereby removing the TDR restrictions on the shock-type excitations. Also, the use of screened rooms for the measurements should not be necessary. One or two experiments of this type are recommended knowing in advance that some probe development work will be necessary and that the complex natural resonances of such targets are not known analytically.

6. Current studies on companion contract (project 710816) show promise of developing resonance extracting procedures which are less sensitive to noisy transient signals. Additional study along these lines is only recommended as found necessary to adjust general techniques to the particular data on this contract.

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